Reducing the Carbon Footprint of Senegalese Cattle Systems through Improved Productivity

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Declaration

I, Gareth Richard Salmon, declare that:

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c) The work has not been submitted for any other degree or professional qualification
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Date of signature:

30/10/2017

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Abbreviations

AEZ	Agro-ecological zone
AFC	Age at first calving
AI	Artificial insemination
C	Carbon
CFA	Central African Franc (1 CFA ≈ 0.0016 USD)
CGIAR	Formerly the Consultative Group for International Agricultural Research
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CP	Crude protein
CSA	Climate Smart Agriculture
DE%	Ration digestible energy, as a percentage of gross energy
DMI	Dry matter intake (kg)
Ei	Emissions intensity (kgCO_2eq/ kg product)
EISMV	Inter-State School of Veterinary Science and Medicine, Dakar, Senegal
FAO	Food and Agriculture Organization of the United Nations
FGD	Focus group discussion
FMD	Foot and Mouth Disease
FPCM	Fat and protein corrected milk
GE	Gross energy (MJ)
GHG	Greenhouse gases (carbon dioxide, methane and nitrous oxide)
GLEAM	Global Livestock Environmental Assessment Model
GNC	Groundnut cake
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
ILRI	International Livestock Research Institute
IPCC	International Panel on Climate Change

LCA	Lifecycle assessment
LSD	Lumpy Skin Disease
MACC	Marginal abatement cost curve
MJ	Mega joule (10^6 joules)
N	Nitrogen
N_2O	Nitrous oxide
NE	Net energy
NGO	Non-government organisation
PC	Purchased concentrate (compound) feed
REG	Ratio of NE available for growth in a diet, to digestible energy consumed
REM	Ratio of NE available in a diet for maintenance, to digestible energy consumed
SDG	Senegal Dairy Genetics project
SI	Sustainable Intensification
SRUC	Scotland's Rural College
SSA	Sub Saharan Africa
Tryps	Trypanosomiasis
VFA	Volatile fatty acid

Thesis abstract

Meat and milk from sub Saharan African cattle systems tend to have high greenhouse gas emissions intensities; this is largely due to low levels of productivity. There is a need to increase production to meet an increasing demand for livestock commodities; driven by growing populations, and growing diet variation, as incomes and urbanisation increase. Without measures to reduce the emissions intensity of production, there will be significant increases in total greenhouse gas emissions. Therefore, cost-effective ways of reducing emissions intensity, whilst increasing productivity should be identified.

This thesis looks to support this by providing an assessment of low-input to semi-intensified cattle production systems in Senegal, West Africa; where cattle populations are growing and efforts are being made to increase domestic milk production. The emissions intensity of protein from current production systems is calculated using a version of the Food and Agriculture Organization's Global Livestock Environmental Assessment Model (GLEAM). Variation in emissions intensity is observed between current systems, which can be largely linked to feed ration quality and levels of protein productivity.

Productivity improving interventions suitable for the study systems are identified, and their application to current systems modelled by altering input parameters within GLEAM. It is suggested that production systems could reduce emissions intensities by applying nutritional and health related intervention packages; through which the varying production systems could abate between 10% and 20% of their total greenhouse gas emissions whilst also making financial savings. A comparison between the current systems of production also suggests that changing the lower productivity systems to match higher producing systems would also offer substantial cost-saving emissions abatement.

The thesis considers the key limitation to the use of GLEAM for modelling the application of nutritional mitigation measures, in that when nutritional improvements are made animal performance does not currently increase. Predicting how animals will respond to improved nutrition is challenging. However, a methodology is discussed, and is shown to have an important effect on the emissions abatement results. Subsequently, the thesis advocates further research to experimentally substantiate animal performance responses when nutritionally limited cattle are given improved feed regimes.

Despite the study livestock keepers showing aspiration to improve the productivity of their herds, with subsequent potential to reduce greenhouse gas emissions, the thesis recognises that the abatement potentials suggested by modelling would be restricted by the reality of production system context and constraints. Key barriers to a realisation of the productivity improvements include: a lack of financial means, limitations to resource access and affordability, and requirement for information and training concerning productivity improving options. For realisation of productivity improvements the current barriers would require further investigation, the thesis helps identify what form interventions should take.

Lay summary

It is widely understood that the rearing of cattle contributes significantly to human caused greenhouse gas emissions, and subsequently to climate change. Based on the production process, protein from cattle systems can have greenhouse gas emissions allocated to it. In turn, each unit of produce (e.g. milk or meat) can have a number of units of greenhouse gas emissions associated with it; this is termed emissions intensity. Globally, emissions intensities vary, largely this is related to protein productivity (for instance cattle milk yields), the higher the productivity, the less emissions required to produce each unit of protein. Sub Saharan Africa has relatively low levels of cattle productivity, therefore has high protein emissions intensities. The region is also experiencing rapidly growing populations, with increasing wealth and urbanisation (diversifying diets); therefore the demand for livestock produce is also increasing. If options to improve productivity are not considered, total greenhouse gas emissions are likely to increase. Therefore, cost-effective ways of reducing emissions intensity, whilst increasing productivity should be identified.

This thesis makes a contribution to this by considering productivity improving options for case study cattle production systems in Senegal, West Africa; where cattle populations are growing and efforts are being made to increase milk production.

Firstly, the greenhouse gas emissions intensity of current production systems is considered; there is substantial variation here, which can largely be related to variation in productivity of the different systems.

Secondly, a process of shortlisting is used to find productivity improving interventions which would be suitable for application to the study production systems, these largely involve improving cattle feed quality and animal health. The application of the interventions is modelled to consider how much emissions could be avoided and how cost-effective such actions would be. The results suggest that livestock keepers could apply interventions that would have both financial benefits to them and reduce emissions. As well as improving the current production systems, it is also suggested that changing lower productivity herds to match the production systems of higher productivity herds, would also be a cost-effective way to reduce emissions and increase productivity.

Predicting how animals' production performance (e.g. milk yields) will respond when their feed is improved is a significant challenge, and a current limitation in the modelling of feed related productivity improving interventions. The thesis discusses this challenge and presents a method to overcome it and include performance improvements in the assessment of interventions. It is shown to have an important influence on results and therefore encourages future research to investigate how the production from under-fed cattle responds to improved feeding.

The livestock keepers in the study systems showed aspiration to uptake productivity improving interventions. However, the thesis also recognises that productivity improvements are limited by barriers which include: a lack of financial means, limitations to resource access and affordability, and requirement for information and training concerning productivity improving options. If productivity is to be improved these must be considered further.

CHAPTER ONE

INTRODUCTION

1.1. The significance of the livestock sector for climate change

Climate change could be regarded as one of the greatest challenges humanity currently faces, and it is human activities that are the key drivers behind the global warming that is being observed (IPCC, 2013). Steinfeld *et al.* (Steinfeld *et al.*, 2006) assessed the full global environmental impact of the livestock sector (including impacts on water, biodiversity, land use and climate). Accounting for 40% of the gross domestic product from agriculture, livestock was stated as being "*responsible for 18% of greenhouse gas emissions*" (Steinfeld *et al.*, 2006). When broken down in to the three principal greenhouse gases (GHG): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), it is evident that the livestock sector is a significant contributor to anthropogenic emissions of CH_4 and N_2O (the relevant results presented in Livestock's Long Shadow are summarised in Figure 1.1.). The 2006 report stimulated considerable research and literature into the impact of livestock with regards to GHG emissions.

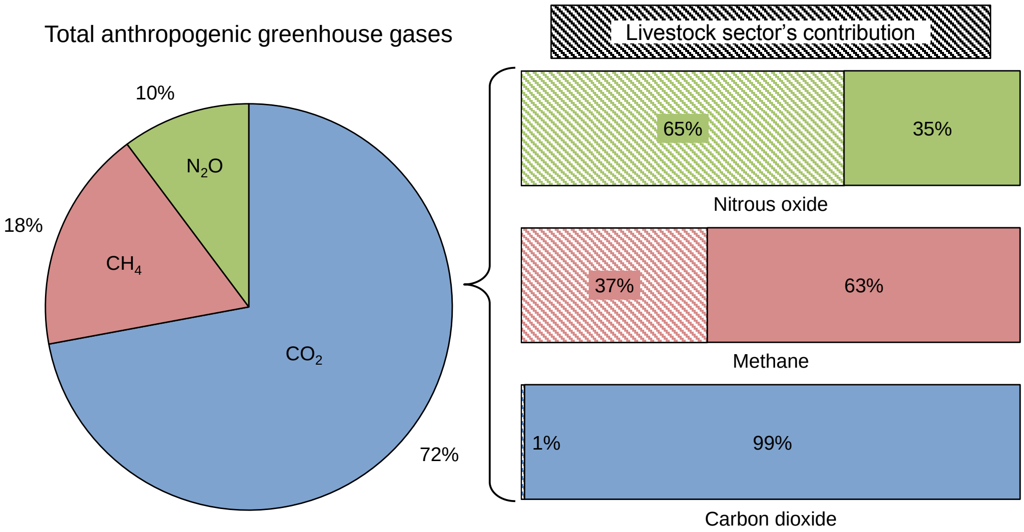

Figure 1.1. The suggested role of the livestock sector in carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions (expressed as CO_2 equivalents). Total anthropogenic emissions are shown on the left, whilst the hatched portion of the right-hand bars show the livestock sector contribution to the individual GHGs. (Summarised from Steinfeld *et al.* (Steinfeld *et al.*, 2006)).

Following this increased interest, both publically and within the scientific community, significant research efforts looked to quantify the GHG emissions associated with livestock production at both global sector and local scales (Arsenault *et al.*, 2009; Beauchemin *et al.*, 2011, 2010; Belflower *et al.*, 2012; Bell *et al.*, 2011; Casey and Holden, 2006; Fiala, 2008; Foley *et al.*, 2011; Gerber *et al.*, 2010; MacLeod *et al.*, 2013; O'Brien *et al.*, 2012; Opio *et al.*, 2013; Pelletier and Tyedmers, 2010; Rotz *et al.*, 2010; Stackhouse-Lawson *et al.*, 2012; Tilman *et al.*, 2011). Many of these studies, particularly those by the Food and Agriculture Organization of the United Nations (FAO) used lifecycle assessments[1] (LCA) to quantify production associated GHG emissions. Often it is recognised that although livestock are a significant contributor, the sector also offers opportunity for GHG emission mitigation. Consequently, in response to the initial negative tone of 'Livestock's Long Shadow' (Steinfeld *et al.*, 2006), in 2013 the FAO published a report entitled *'Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities'* (Gerber *et al.*, 2013b). As well as confirming the contribution of livestock to climate change (reporting the livestock sector to be responsible for 14.5% of anthropogenic GHG emissions), the report highlighted the opportunity within the livestock sector to mitigate climate impacts; making statements such as *"a 30% reduction of GHG emissions would be possible, for example, if producers in a given system, region and climate adopted the technologies and practice currently used by the 10% of producers with the lowest emission intensity"* (Gerber *et al.*, 2013b). Although authoritative statements like this need to be interpreted carefully, they draw attention to the fact that efficiency of production is the key consideration. Reductions in emissions are *"within reach"*, and it is efficiency of production that can provide both environmental and economic benefits (Gerber *et al.*, 2013b).

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[1] Life Cycle Assessment (LCA), defined in ISO standards 14040 and 14044 (ISO, 2006a, 2006b), describes a methodology used to evaluate environmental impact of production, identifying resource and emissions intensive processes in product lifecycles. A holistic assessment accounts for all inputs and outputs within a defined system boundary, so can identify approaches to reduce environmental burdens whilst avoiding shifting burdens between different stages of production. For further information see Thomassen *et al.* (2008).

1.2. The variation in greenhouse gas emissions intensity

It is recognised both globally (Caro *et al.*, 2014; Opio *et al.*, 2013), and at more local scales (Rotz *et al.*, 2010; Stackhouse-Lawson *et al.*, 2012), that variation in the efficiency of production can lead to variation in GHG emissions intensity (Ei, the GHG emissions per unit of livestock product, for example kg of carbon dioxide equivalents[2] per kg of milk (kg CO_2eq/kg milk). For example, Opio *et al.* (2013) reported regional average Ei for milk ranging from 1.7 kg CO_2eq/kg milk, for industrialised regions, to 9 kg CO_2eq/kg milk for sub Saharan Africa (SSA) (Figure 1.2.). This variation was closely linked to differences in milk yield (Figure 1.3.). When per animal yield was higher, per animal GHG emissions were also higher, however GHG Ei declined. Authors have argued that pathways to increased food production could also offer GHG mitigation (Beauchemin *et al.*, 2011; Bell *et al.*, 2011), predominantly in areas where yields were particularly low (e.g. in SSA) (Gerber *et al.*, 2011).

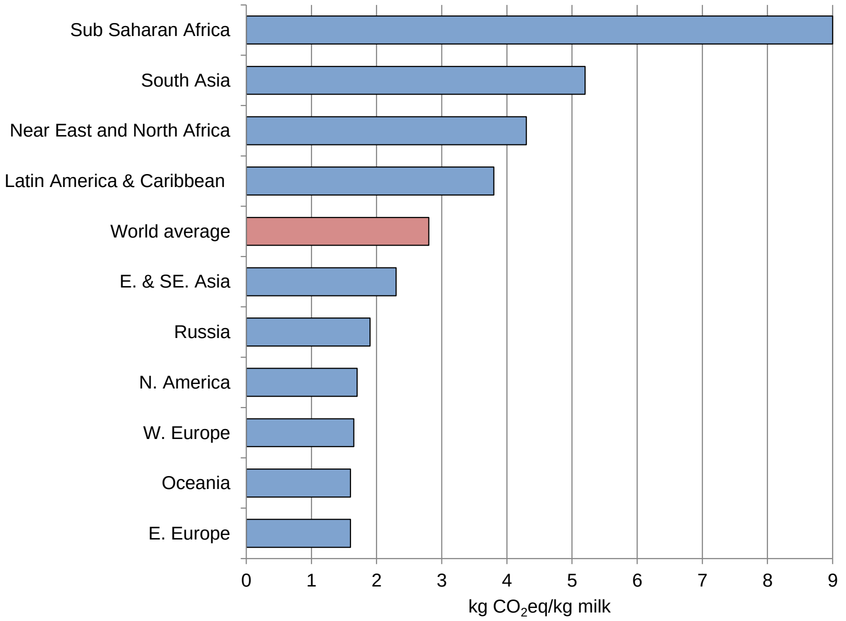

Figure 1.2. Regional average emissions intensity for cattle milk (in 2005). (Adapted from Opio *et al.* (2013)).

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[2] Carbon dioxide equivalent (CO_2eq) is the volume of CO_2 emissions that would cause the same radiative forcing as the emission of a mix of GHGs all multiplied by their respective global warming potentials (GWP); this takes into account the time different gases remain in the atmosphere. GWP is the 100 year time horizon for gases relative to CO_2. CO_2 = 1; CH_4 = 28; N_2O = 265 (IPCC, 2014).

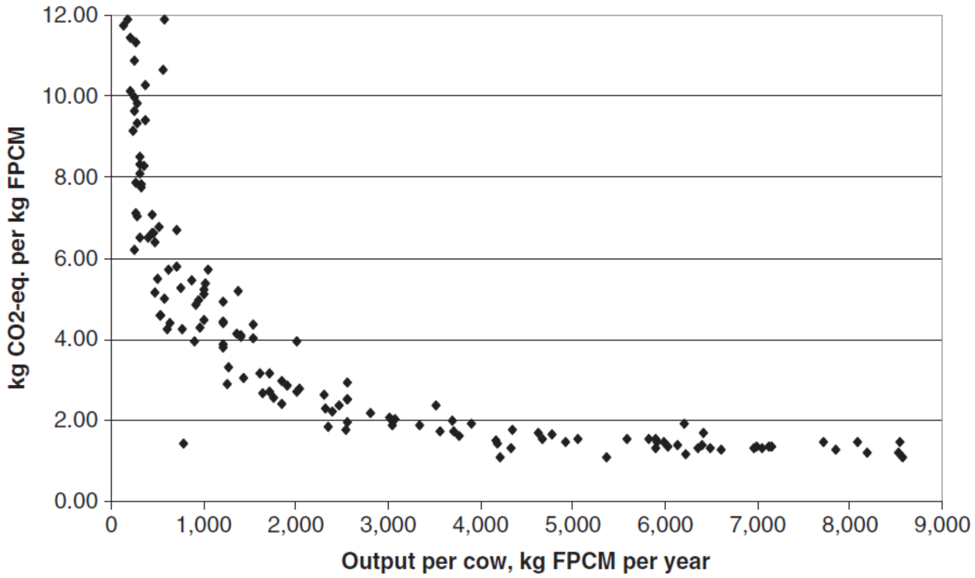

Figure 1.3. Relationship between greenhouse gas emissions intensity (y-axis) and milk output per cow (x-axis). Each dot represents a country average. FPCM: fat and protein corrected milk. (Gerber *et al.*, 2011).

1.3. Methods for assessing GHG emissions from farm systems

The FAO quantification of GHG emissions associated with livestock production are based on the Global Livestock Environmental Assessment Model (GLEAM), more information concerning the use of GLEAM can be found in section 5.1.. However, it is important to note that other models have been developed for the quantification of GHG emissions in livestock production as well as the quantification of GHG emission mitigation potentials. Models are generally scaled at a farm level, to effectively consider management decisions which could lead to GHG emissions mitigation (Del Prado et al., 2013). For detailed reviews of such approaches see del Prado *et al.* (2013) and Schils *et al.* (2007).

1.4. The significance of cattle production in sub Saharan Africa

SSA made progress in improving food security over the last two decades; between 1990 and 2015 the prevalence of population undernourishment decreased by 31% (FAO, 2015); despite this SSA still had 220 million people undernourished in 2014-16 (44 million more than in 1990) and undernourishment prevalence saw an increase in 2016 (FAO *et al.*, 2017). Considering this undernourishment and the impact of SSA's sustained high population growth rate (2.7% annually) (FAO *et al.*, 2015; Gerland *et al.*, 2014), there is a continually growing demand for effective nourishment. Livestock produce will play a key role in meeting this demand (Alexandratos and Bruinsma, 2012), as improving incomes (Pinkovskiy and Sala-i-Martin, 2014) and urbanisation (with increasing diet variation) (FAO, 2002) drive '*the livestock revolution*' (Delgado *et al.*, 1999). Chicken and pig production is expected to be important in meeting this demand for meat; however ruminants are also expected to increase substantially for both beef and milk production (Herrero *et al.*, 2008). Over 230 million cattle (Herrero *et al.*, 2008) already support a large proportion of the poor and food insecure population (Gerber *et al.*, 2010; Herrero *et al.*, 2013a; Maichomo *et al.*, 2009). In addition to protein production, the significance of cattle in SSA is increased by other common functions, including a store of wealth and cultural roles (demonstration of status, ceremonial function, and as dowries) (Herrero *et al.*, 2013a, 2009; Thornton, 2010). As well as supporting mixed cropping-livestock systems through provision of draught power, organic fertiliser as manure, and adding value to consumed crop residues (Herrero *et al.*, 2013a; Jackson and Mtengeti, 2005; Tano *et al.*, 2003).

If efforts are not made to reduce the characteristically high Ei of SSA cattle production (Figure 1.2.), meeting the demands of food security will increase total GHG emissions; for instance CH_4 emissions from SSA ruminants are forecast to increase by 42% by 2030 (Herrero *et al.*, 2008). Yet various authors have suggested that the relevant systems of production have potential for productivity improvement (Gollin, 2014; Herrero *et al.*, 2014, 2013a; Jayne *et al.*, 2014). Therefore, there is significant theoretical potential for SSA cattle systems to have a role in Sustainable Intensification and Climate Smart Agriculture (Box 1.1.). This thesis aims to use a case study of cattle production in Senegal to investigate this potential. The Senegal Dairy Genetics (SDG) project (Box 1.2.) gathered extensive longitudinal data (data collected from a population over a given time period), providing an opportunity to analyse GHG emissions and productivity from a variety of cattle systems.

Box 1.1. Sustainable Intensification and Climate-Smart Agriculture

Sustainable intensification (SI) and climate-smart agriculture (CSA) are two common paradigms in agricultural development.

The term SI has existed for over two decades, its origins lie in the realisation of the increasing demand for food and the environmental impact agricultural production entails (Garnett *et al.*, 2013). Hence the objective was ‘originally conceived as an approach to produce higher levels of output from the same area of land while decreasing the negative environmental impacts of agricultural production and increasing the provision of environmental services’ (IIED, 2015). Despite these positive beginnings, SI has received criticism for being too production focused, used by certain actors to repackage intensive production models and neglecting any social or economic elements (Campbell *et al.*, 2014; IIED, 2015).

Climate-smart agriculture is a more recent concept similarly defined to assist in responding to the challenges facing agriculture (population and food demand growth) (FAO, 2013). However, in addition CSA specifically considers the roles agriculture will have in economic growth, poverty reduction, and climate change adaptation and mitigation. The CSA concept integrates the economic, social, and environmental dimensions of sustainable development to address this challenge (Campbell *et al.*, 2014; FAO, 2013). The three pillars are:

1. Increase production and incomes sustainably
2. Adapt systems and increase resilience in the face of climate change
3. Reduce greenhouse gas emissions

An example of where the CSA concept has been useful is the FAO Mitigation of Climate Change in Agriculture (MICCA) Programme development of a ‘menu’ of CSA practices for Tanzanian and Kenyan smallholders. Participatory assessments and a consultative process within specific pilot projects identified practices that match the agro-ecological and socio-economic scenarios. Farmers identified existing practices and their impacts, and then designed the ‘menu’ of CSA practices that could be integrated into their systems. Extension approaches and incentive mechanisms were used to build capacity and promote uptake (FAO, 2013).

Fundamentally SI and CSA are closely linked concepts; both have emphasis on food production productivity improvements. For instance CSA has more defined focus on both climate change adaptation and mitigation, however SI is also a key aspect of realising adaptation and mitigation (Campbell *et al.*, 2014). Both concepts should be included in development efforts towards food security, however neither should be considered solutions; instead they should both be recognised as guiding frameworks as part of integrated approaches (Campbell *et al.*, 2014; Garnett *et al.*, 2013; IIED, 2015).

1.5. Cattle systems in Senegal

The rearing of livestock is an essential sector of the Senegalese economy, supporting over a third of the population and contributing to around 4.8% of the gross domestic product (Ministère du Commerce, 2013; Seck and Fadiga, 2016). Due to this reliance on livestock, particularly by those in poverty, the sector is recognised as an opportunity for poverty alleviation and deserving of appropriate policy support (Roland-Holst and Otte, 2007). Senegal's cattle population is now estimated to be over 3.5 million (FAOSTAT, 2017), and since 2000 has been following a similar upward trend as the Global cattle population (Figure 1.4).

Box 1.2. The Senegal Dairy Genetics Project

The Senegal Dairy Genetics (SDG) project aimed to *"identify and promote use of the most appropriate dairy cattle breeds or crossbreeds in selected production systems in Senegal"* (Marshall *et al.*, 2016b). The project demonstrated that genetics and improved management can significantly benefit households, with the highest profit scenarios seen for those households keeping Zebu by Bos Taurus crossbreeds. Crossbreeds are both well adapted to the challenging environment and have increased productivity. Management is also important in allowing genetic productivity potential to be expressed. The research aimed to support stakeholders with decisions regarding which breeds to keep or promote. Recommendations from the study included (Marshall *et al.*, 2016b):

1. Crossbreed indigenous Zebu by Bos Taurus semen should be made available to cattle keepers through public and private artificial insemination (AI) programs.
2. Appropriate training on management practices (feed, animal housing and AI preparations) should be made available, enabling improved genotype keeping households to achieve increased profits.
3. Means, such as access to credit, should be available to help with initial investment to enable the rearing of crossbreeds, particularly for low wealth groups.

Further details of the study sites are included in Chapter two.

The SDG project was funded by the Finnish Ministry of Foreign Affairs (via the FoodAfrica program) and the CGIAR Research Program on Livestock and Fish. The project was led by the International Livestock Research Institute.

For further information see the SDG project website:
https://senegaldairy.wordpress.com/.

Cattle are largely reared in low-input agro-pastoral or pastoral systems (Dieye *et al.*, 2008; Kazybayeva *et al.*, 2006), however there is an increasing number of more intensive peri-urban systems (Bouyer *et al.*, 2015; Gning, 2004; Yameogo *et al.*, 2008). Agro-pastoral and pastoral systems are traditional and prevalent across Senegal (Seck and Fadiga, 2016). These heavily climate reliant systems predominantly use indigenous breeds, graze communal pasture and supplement rations with crop residues; production slows dramatically through the dry season (Ndiaye, 2007). The peri-urban systems typically use imported exotic breeds, or indigenous by exotic crossbreeds, reared under improved management (Dieye *et al.*, 2008). These peri-urban systems include a minority of intensive commercial herds; generally private operations located around Dakar and the urban demand for milk and dairy products. There are also smaller farms owned by higher earning city dwellers, with additional income to afford the increased inputs required to rear crossbreeds, these are located around Dakar and Thiès (Gning, 2004; Seck and Fadiga, 2016).

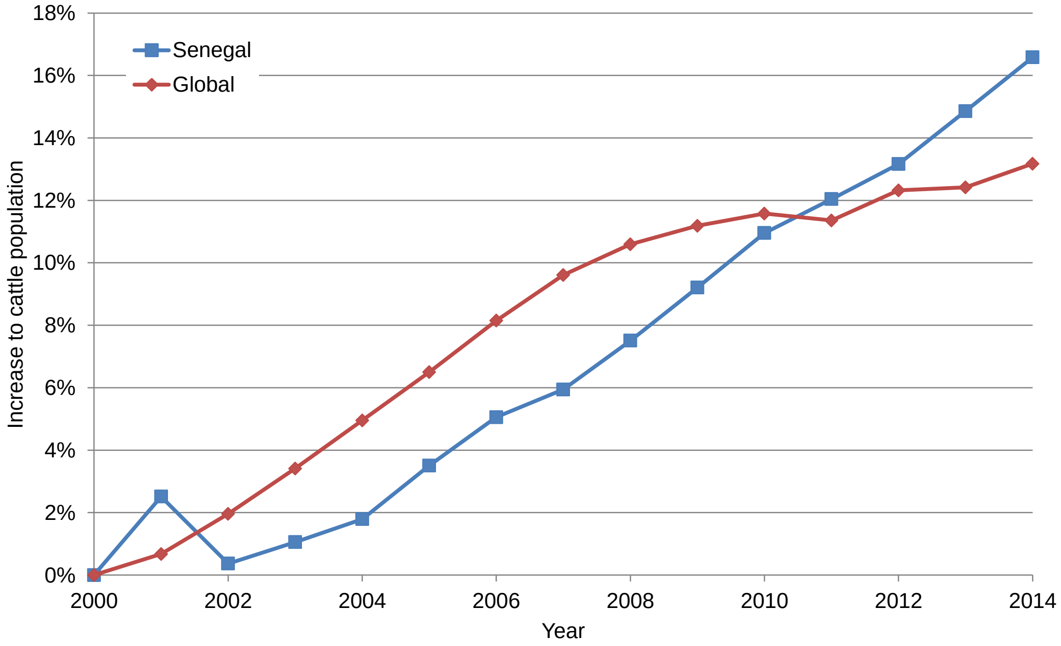

Figure 1.4. Global and Senegal cattle population trends from a baseline at year 2000 (FAOSTAT, 2017).

Historically Senegal has relied on imports for domestic dairy consumption (Ndiaye, 2007). Figure 1.5. shows the trends in domestically produced, exported and imported dairy products, and suggests a decline in reliance on imports since 2009. Whether or not this is a sustainable trend, after decades of neglect the Senegalese government have shown awareness and some ambition to improve domestic dairy producers' productivity and competitiveness. For instance the initiation of a National Program for Livestock Development in 2005, seeks to reach self-sufficiency in animal products and stakeholder economic strength by 2026 (Seck and Fadiga, 2016). Evidently, Senegalese cattle systems provide a scenario worthy of investigation into potential productivity improvements, and along with the availability of real data (from the SDG project) produced the incentive for this PhD thesis.

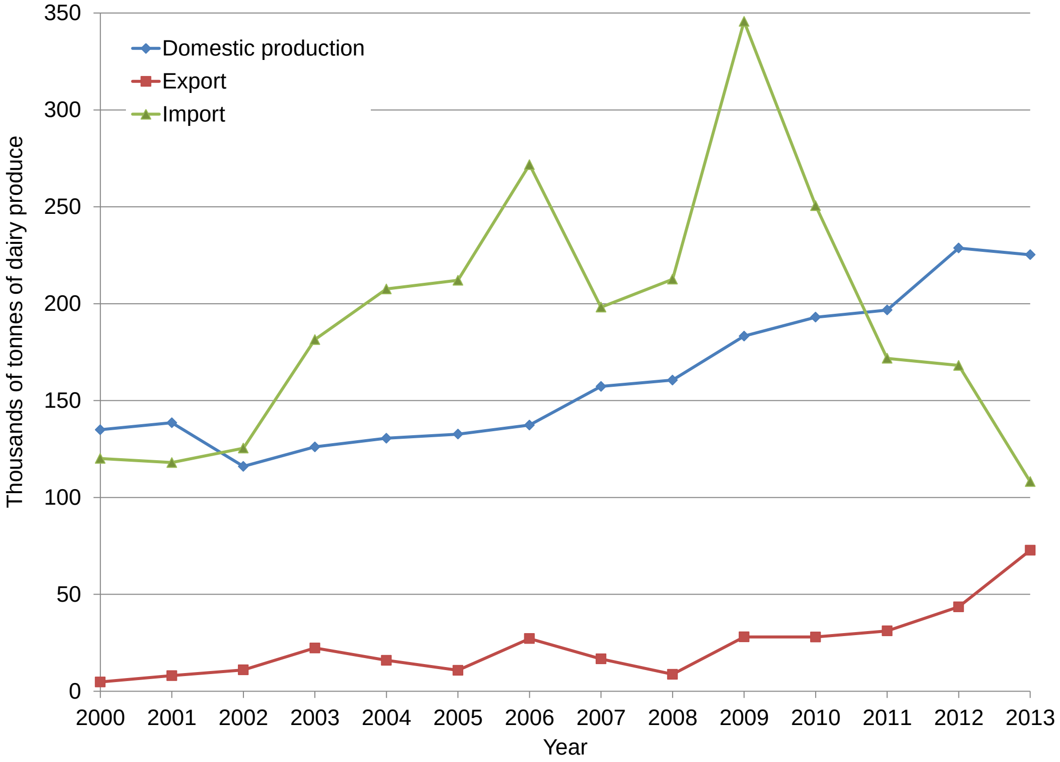

Figure 1.5. Trends of domestic consumption, export and import of dairy products in Senegal. Derived from FAOSTAT data (FAOSTAT, 2017).

1.5.1. Senegal's livestock GHG emissions

Annually, Senegal emits around 32 million tonnes of CO_2eq ($MtCO_2eq$) (0.07% of global total) (USAID, 2016). The majority of Senegal's emissions are from agriculture (36% in 2011); with energy (27%), land-use change (22%), waste (9%) and industrial processes (7%) making up the remainder. Enteric fermentation from ruminant livestock contributes to approximately a third the agricultural emissions. From 1990 to 2011 Senegal's total emissions increased by 8 $MtCO_2eq$, with agricultural emissions increasing by 36% (USAID, 2016).

In 2015 Senegal submitted their Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC). Senegal's INDC is part of the Emerging Senegal Plan (a framework of economic and social policy to realise economic well-being by 2035). The INDC gives detail of the implementation of activities aiming to reduce GHG emissions. The agricultural activities are focused on manure management, rice cultivation, cultivated soils, organic fertilisers and forest planting; and suggest unconditional reductions in agricultural emissions by 0.19% by 2030, with conditional reductions (requiring greater funding) of 0.63% by 2030 (for comparison energy emission reduction targets for 2030 are 6% unconditional and 31% conditional). There is limited reference to the livestock contribution, but measures including the development and support of pastoral systems, breeding options and the improvement of production and animal health are referenced (Gouvernement du Senegal, 2015). In 2017 Senegal became the 3rd African nation (49th nation) to join the Global Research Alliance on Agricultural Greenhouse Gases (Global Research Alliance, 2017)

1.6. Thesis aims and objectives

It is widely understood that cattle production systems are a significant contributor to GHG emissions, and that due to low levels of productivity SSA stands out as a concentration of high Ei. The demand for cattle production is predicted to increase and under a business-as-usual scenario this will lead to significant rises in total GHG emissions. However, past authors have suggested that SSA production systems have potential for productivity improvements, offering ‘win-win’ opportunities to improve food security and reduce GHG emissions. This thesis contributes to this literature by presenting a methodology and results to quantify this abatement potential at a herd level. The SDG project data offers a rare opportunity to use a detailed case study to consider options to improve system productivity, and understand what is most appropriate for the specific livestock keepers, with consideration to their priorities and barriers. This thesis will support decision makers and stakeholders to pursue climate-sensitive options. The specific aims of this thesis are to:

a. Define the Ei of the current (baseline) case study production systems
b. Identify a set of mitigation measures that could be applied to the case study systems
c. Calculate the abatement potential and cost-effectiveness of the measures
d. Identify potential barriers to the adoption of cost-effective measures

1.7. Thesis structure

Chapter two

Chapter two introduces details of the current systems of cattle production for the case study households in Senegal.

Chapter three

Chapter three describes fieldwork carried out in relation to further case study specific context setting and mitigation measure shortlisting.

Chapter four

Chapter four explains the process of shortlisting mitigation measures for application to suggest productivity improvement for the baseline systems.

Chapter five

Chapter five presents the first round of modelling to calculate both the baseline Ei of production and the GHG abatement potential of mitigation measure application. Modelling results and the method limitations for this first round of modelling are also discussed. Chapter five also formed a journal paper (available in Appendix F).

Chapter six

Chapter six presents a proposed methodology for estimating changes in animal performance when their nutrition is improved. Mitigation measure application was then remodelled with the inclusion of this estimation and the influences of this on results are discussed.

Chapter seven

Chapter seven discusses the potential for productivity improvement and emission abatement by households switching cattle breed types.

Chapter eight

Chapter eight summarises results and discusses them in a broader context.

CHAPTER TWO

STUDY AREA AND PRODUCTION SYSTEMS

Chapter two introduces the study area and production systems. The majority of the reported information was collected through surveys as part of the SDG project (Box 1.2.), or was derived by the author from the information gathered through the SDG surveys.

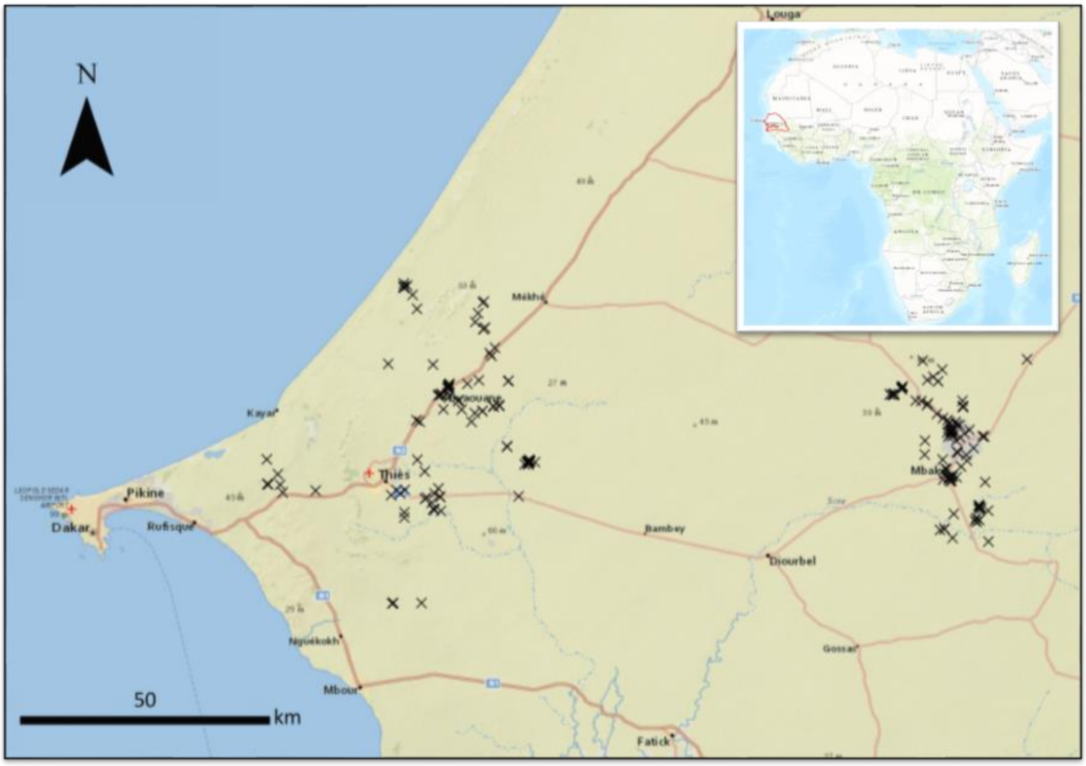

Figure 2.1. Map of western Senegal, with the location of Senegal in West Africa shown on the smaller map. Crosses indicate the approximate location of the 220 households from which data were gathered as part of the SDG project and the subject of this thesis. Sites are located around the cities of Thiès and Mbaké.

2.1. Geography, climate and cattle

Senegal is located at the most westerly tip of Africa, between 12.5 and 16.5 degrees north of the equator. The country has a tropical climate with two seasons; rains from June to October and a dry season, with dry harmattan winds, from November to May (Seck *et al.*, 2016). Soils are predominantly poor, rainfall irregular and droughts increasingly common. With the majority of cattle systems dependent on the rains, production is significantly reduced through the dry season and extended droughts (Ndiaye, 2007). The country is split into seven large agro-ecological zones (AEZs), each with unique physical and human population characteristics (Seck *et al.*, 2016).

Of these AEZs it is the Peanut Basin (*Bassin arachidier*) (with a total area of 27,407 km^2, and human and cattle populations of 1 million and 228,000, respectively (Williams *et al.*, 2004)) which includes the administrative regions of Thiès and Diourbel (Mbaké). The climate of Thiès and Diourbel can be characterised as Sahelian, and the average annual rainfall is 663 mm (Fall *et al.*, 2006). This thesis is largely based on data gathered by the SDG project (Box 1.2.) from 220 cattle keeping households (with more than 3000 animals in total, over 2 years) in these regions. Cattle are largely reared in low to medium input agro-pastoral systems, reliant on natural pasture and crop residues, as well as some limited use of feed concentrates (Tebug *et al.*, 2016).

2.2. Assignment of households to defined categories

The 220 households were purposefully selected by the SDG project to guarantee that a spread of the existing cattle breed types in the region were included in the sample. Each of the households were assigned to one of seven categories (Tebug *et al.*, 2016), based on both herd breed type and management level.

2.2.1. Breed types

Four main breed types were identified based on either farmer recall information (farmer defined breed type of animals' grandparents) or if available, genotype information (the SDG project genotyped 128 lactating females). The breed types are specified in Table 2.1. and example animals are shown in Figure 2.2.. Breed types included (Tebug *et al.*, 2016):

a) Indigenous Zebu, mainly Zebu Gobra and Zebu Maure (going forward this is abbreviated to IZ)

b) Indigenous Zebu crossbred with Zebu Guzerat (going forward this is abbreviated to IZ x GZ), Guzerat are a recent introduction from Brazil, developed from Kankrei cattle originally from India (Mariante *et al.*, 1999)

c) Indigenous Zebu crossbred with recently introduced Bos Taurus (going forward this is abbreviated to IZ x BT), Bos Taurus are mainly high milk yielding Montbeliard or Holstein Friesian

d) Indigenous Zebu crossbred with a higher proportion of Bos Taurus (going forward this is abbreviated to BT)

Table 2.1. Breed type definition criteria. Households were categorised to a breed type by the dominant breed of animals in their herd, based on farmer recall information or genotyping.

Breed type	**Based on proportion of IZ, GZ, BT**		**Brief description**	**HH (%)**
	Farmer recall	**Genotyped**		
IZ	100% IZ	88-99% IZ	Lowest productivity, greatest resilience to local environment	55
IZ x GZ	50-75% IZ, 25-50% GZ	39-86% IZ, 13-61% GZ		18
IZ x BT	50-75% IZ, 25-50% BT	38-84% IZ, 13-61% BT	Improved productivity, maintain resilience to local environment	21
BT	0-25% IZ, 75-100% BT	0-36% IZ, 63-98% BT	Highest productivity, lowest resilience to local environment	6

IZ = indigenous Zebu; IZ x GZ = indigenous Zebu crossbred with Zebu Guzerat; IZ x BT = indigenous Zebu crossbred with Bos Taurus; BT = indigenous Zebu crossbred with a higher proportion of Bos Taurus; HH = households

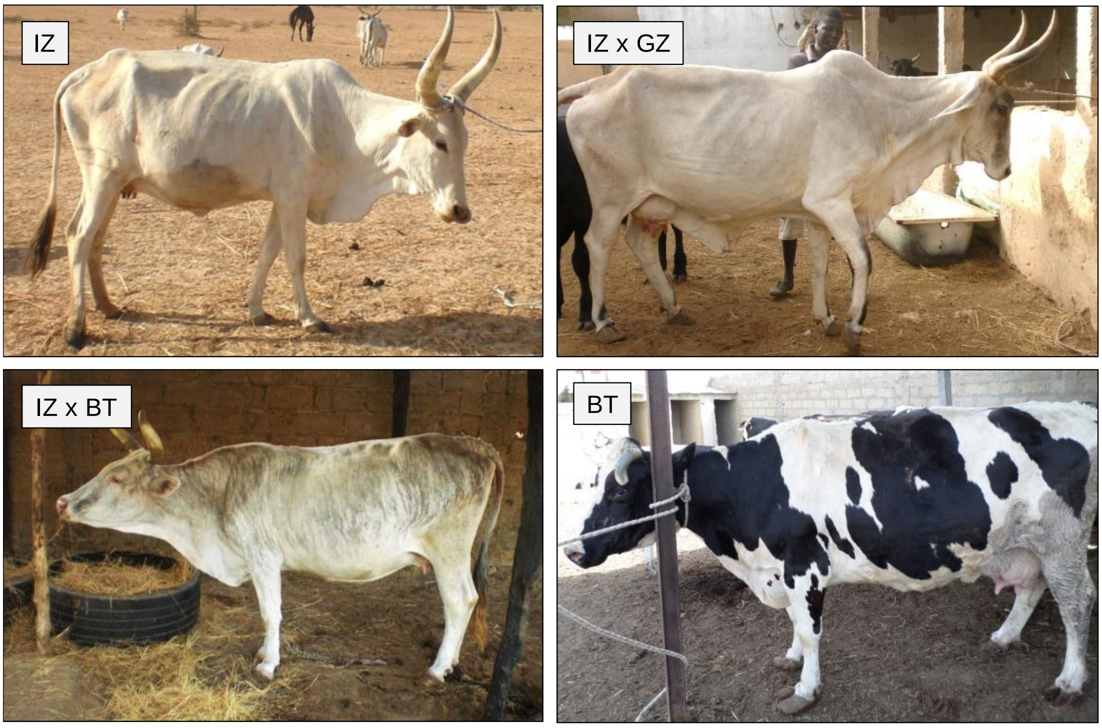

Figure 2.2. Examples of cattle from each defined breed type. (Photo credit: ILRI)

2.2.2. Management input levels

Households within each breed type (Table 2.1.) were also categorised by management input level. The household annual spend on cattle feed was used as a proxy for management input and enabled direct comparison of management across breed types (Table 2.2.). Only one level of management was identified for the BT breed group.

Table 2.2. Household categories, defined by both breed type and management level. Household annual spend on cattle feed is the proxy for management input level, with increasing number of '+' signs indicating increasing level of management input.

Breed group	Management input level	Households (%)
IZ	+	27
IZ	++	27
IZ x GZ	+	9
IZ x GZ	++	9
IZ x BT	++	10
IZ x BT	+++	10
BT	++++	6

2.3. Study household demographical characteristics

2.3.1. Household age and gender profile

Households have on average 18 people, the age and gender of which are illustrated in Figure 2.3.; gender is split evenly, whilst age is more skewed. Over 60% of household members are under the age of the eighteen, whilst only 5% are over the age of sixty; this is consistent with the reported life expectancy (around sixty years) for the region in 2015 (WHO, 2017).

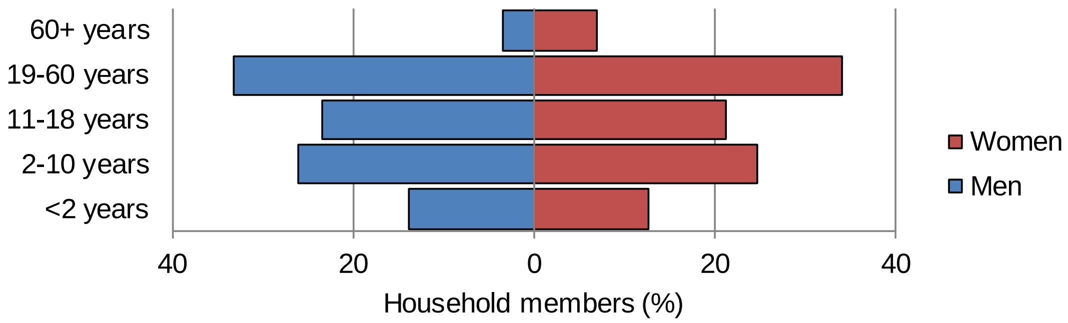

Figure 2.3. Household average age and gender profile (220 households). Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.3.2. Household level of education

Figure 2.4. shows the highest level of education within each study household. Evidently, Koranic schools are the dominant form of education. These institutions are for the study of Islamic theology and religious law, typically attached to mosques. Koranic schools are commonplace in West Africa, often filling the gap or in combination with limited access to formal education (Bah-Lalya, 2015; Goensch, 2016). However, previous authors have suggested Koranic schools must overcome several challenges (including curriculum, teacher training and motivation, student motivation, cultural or political bias and funding) before they can be deemed an appropriate form of education and contribute towards Millennium Development Goals (Bah-Lalya, 2015).

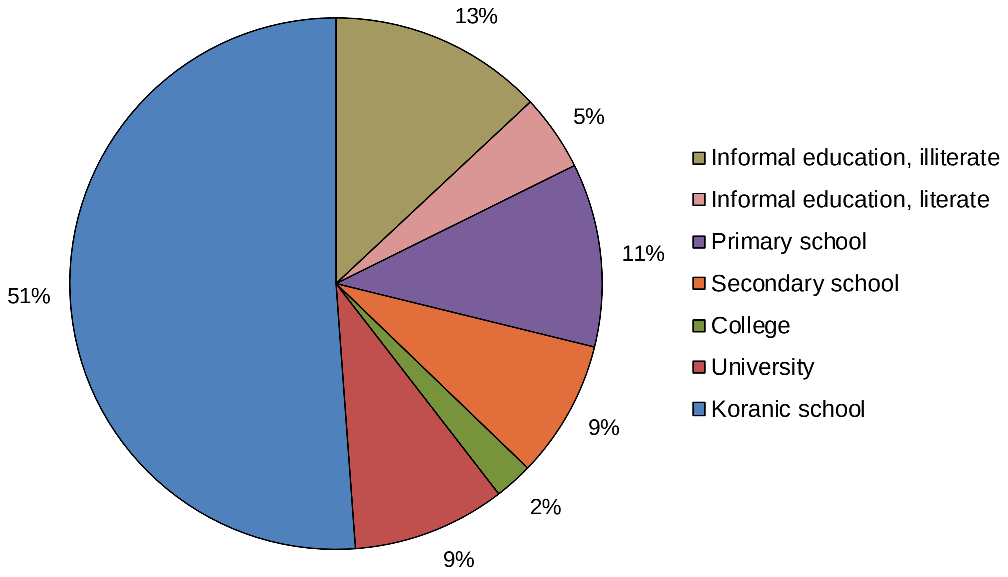

Figure 2.4. Study household heads’ (%) highest level of education (220 households). Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.3.3. Responsibility for cattle systems

Figure 2.5. illustrates how households define gender roles relating to responsibility for cattle rearing; including decision making, labour, payments and income control. Largely, cattle rearing enterprises appear to be the responsibility of men. However, milking, milk processing and milk sales (including control of income) appear to be more the responsibility of women (a common theme in SSA (Chagunda *et al.*, 2015; Kimaro *et al.*, 2013)). This could suggest potential for better household welfare following production improvements, as women often spend more on food and education than men (Bayemi and Webb, 2009; Mullins *et al.*, 1996; Pretty *et al.*, 2011)). However, there is also evidence that as production systems become more intensive (e.g. using more exotic breeds) men become increasingly involved and take more responsibility (Herrero *et al.*, 2013a), reducing the roles of women in the system.

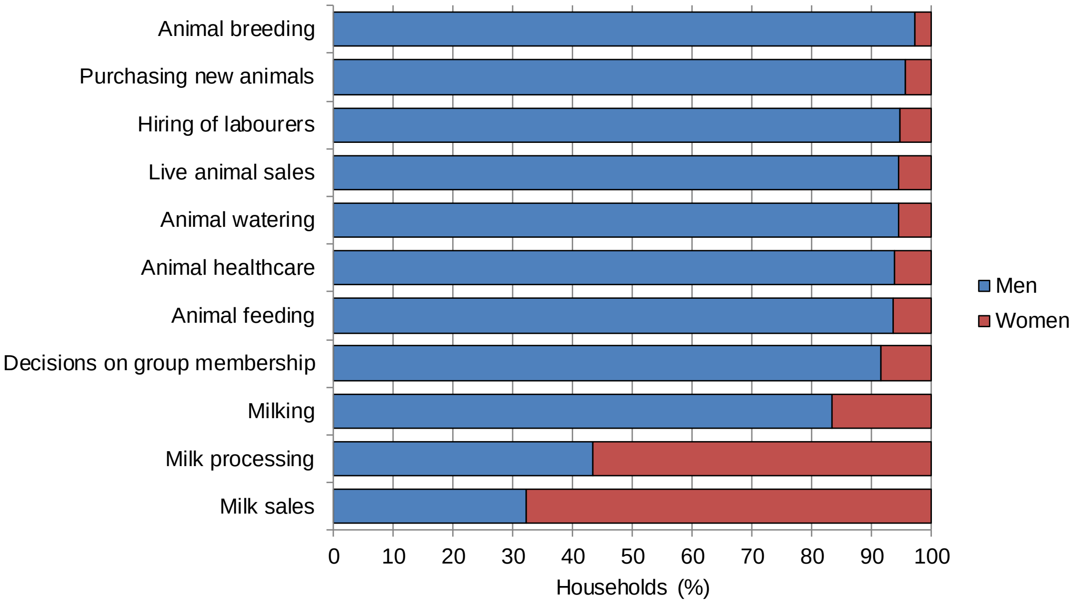

Figure 2.5. Proportion of households with different gender roles for various responsibilities relating to cattle rearing (220 households). Information gathered through SDG baseline survey questions answered by both the household head man and household head woman (in 2013).

2.4. Household income and livelihood

2.4.1. Total household income

Figure 2.6. shows the distribution of households by total monthly income, as reported by the household head. An annual income per adult of less than 225,909 Central African Francs (CFA) (based on average study household structure[3] this equates to 131,000 CFA per household per month) suggests a household is in poverty, whilst an annual income per adult of less than 141,521 CFA (based on average study household structure[3] this equates to 83,000 CFA per household per month) suggests a household is in extreme poverty (Van den Broeck *et al.*, 2017). Almost 50% of households are close to, or above, the poverty line; whilst over 30% of households are likely to be in extreme poverty.

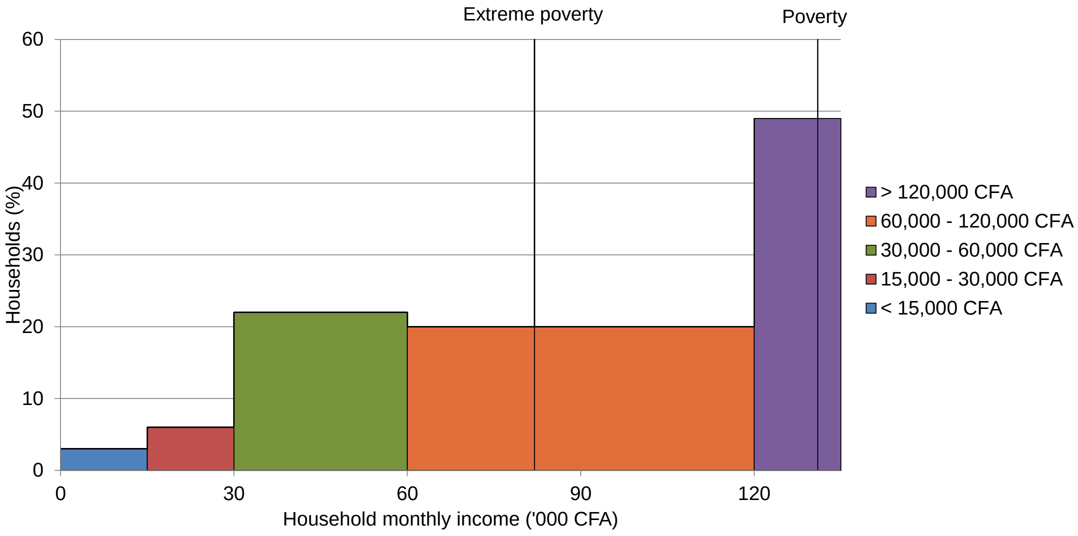

Figure 2.6. Distribution of study households by monthly household income. Income is in Central African Francs (CFA), with an approximate exchange rate of 1 CFA = 0.0016 USD. Vertical lines indicate extreme poverty (income below this suggests a household is in extreme poverty) and poverty (income below this and above extreme poverty suggest a household is in poverty). Information gathered through SDG baseline survey questions answered by the household head (in 2013).

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[3] On average study households in 2013 had seven adults, based on an adult being between the ages of sixteen and sixty.

Study households practice Islam, but identify themselves as different ethnic groups (57% Wolof, 26% Fula, 13% Serer, and 4% Toucouleur) (Box 2.1.). Figure 2.7. shows that amongst study households those of Wolof ethnicity have the largest proportion in the highest income bracket, whilst other ethnicities (particularly Serer and Fula) have a greater proportion in the lower income brackets.

Box 2.1. Ethnic groups of Senegal

Wolof - Traditionally sedentary farmers (Ejlertsen *et al.*, 2013), and accounting for 43% of Senegal's population. They control a large proportion of the countries commerce (Kane, 2009).

Fula (Peul/Fulani) - Widespread across West Africa, and account for around 24% of Senegal's population (Kane, 2009). Fula are traditionally nomadic pastoralists, but increasingly settle leading to conflict with crop farmers (Dongmo *et al.*, 2012; Ejlertsen *et al.*, 2013).

Serer - Account for around 14% of Senegal's population (Kane, 2009).

Toucouleur - A culturally distinct branch of Fula and account for around 10% of Senegal's population (Kane, 2009).

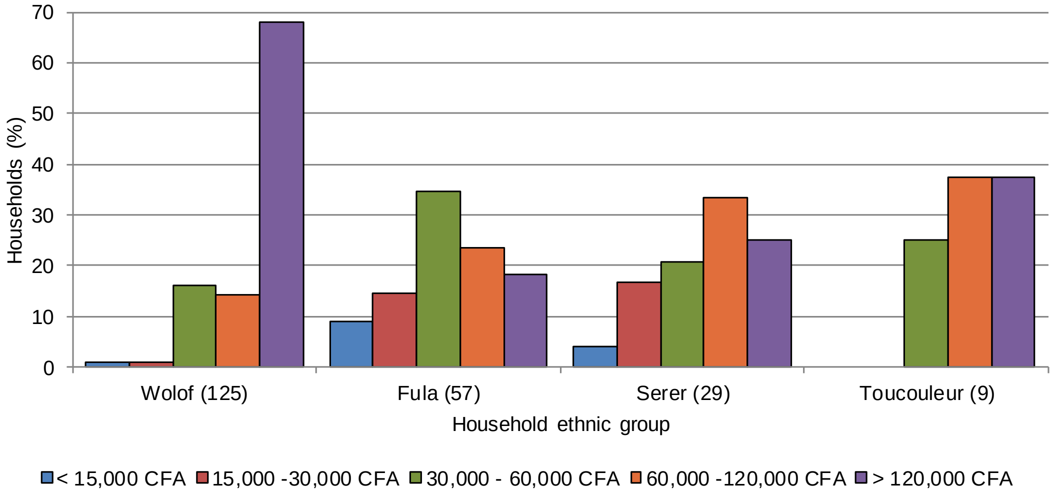

Figure 2.7. Distribution of study households by monthly household income and ethnic group. Income is in Central African Francs (CFA), with an approximate exchange rate of 1 CFA = 0.0016 USD. The number in brackets indicates the total number of households in each ethnic group. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.4.2. Sources of household income

Figure 2.8. demonstrates that for the majority of households (76%) the rearing of dairy cattle does not represent the primary source of household income, instead it is a key secondary source of income (for 46% of households). This is likely due to many of the study households being in close proximity to urban centres, and the employment and income opportunities these offer (Goldsmith *et al.*, 2004). This also suggests that a number of the study households could be defined as semi-intensified, peri-urban cattle systems owned by higher earning people, as mentioned in Chapter one. For almost a third of households the primary income source is from a form of cropping (food or cash crops), this suggests that at least a third of households use agro-pastoral systems.

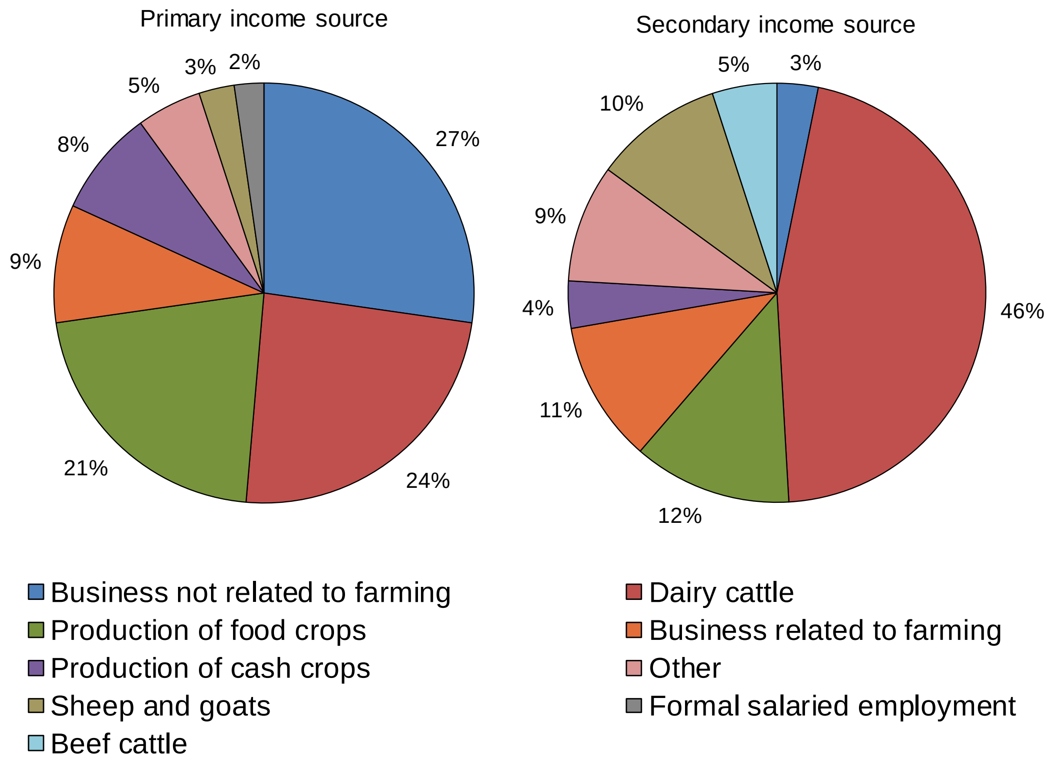

Figure 2.8. Households' (%) primary and secondary sources of income. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.5. Households’ cattle information

2.5.1. Reasons for rearing cattle

Figure 2.9. shows that rearing cattle for income and consumption of milk, and income from animal sales, is important for study households (the primary reason for 39% of households). However, it is also important to recognise that for 27% of households the primary reasons for rearing cattle are those of cultural values (including prestige and status, and a passion or tradition for cattle rearing). Whilst 15% of households keep cattle primarily as a store of wealth or insurance. This multi-functionality of cattle in SSA is widely recognised (Ejlertsen *et al.*, 2013; Udo *et al.*, 2016; Weiler *et al.*, 2014).

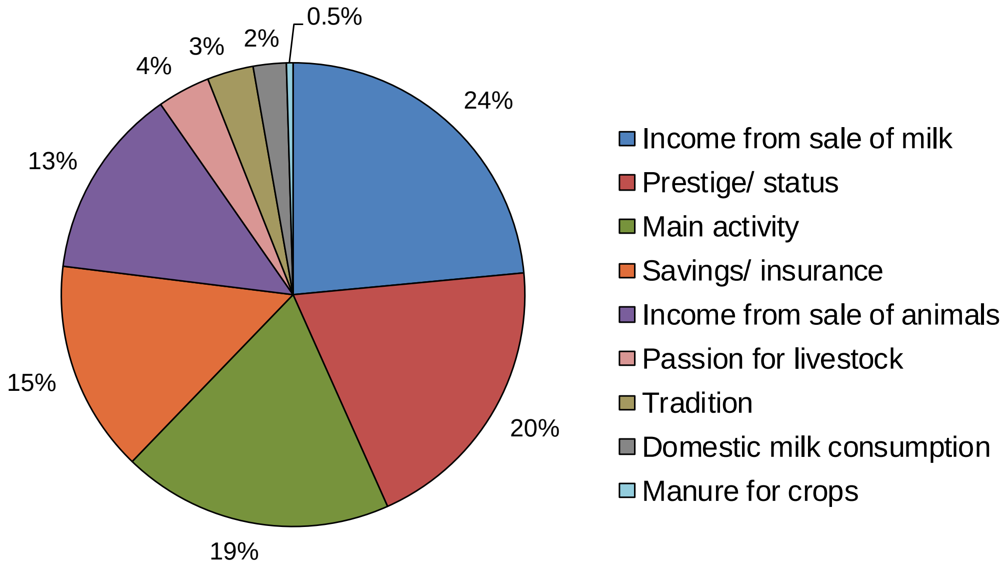

Figure 2.9. Households’ (%) primary reason for rearing cattle. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

Ethnic group also showed some influence on the most common reason households referenced for rearing cattle (Figure 2.10.). Wolof households clearly value the income from milk sales. Whilst other ethnic groups appear to have greater value for the multi-functionality of cattle; including tradition, animals as a store of wealth or insurance and income generated from animal sales. Responses suggest that Fula households have the greatest reliance on cattle rearing to generate livelihoods.

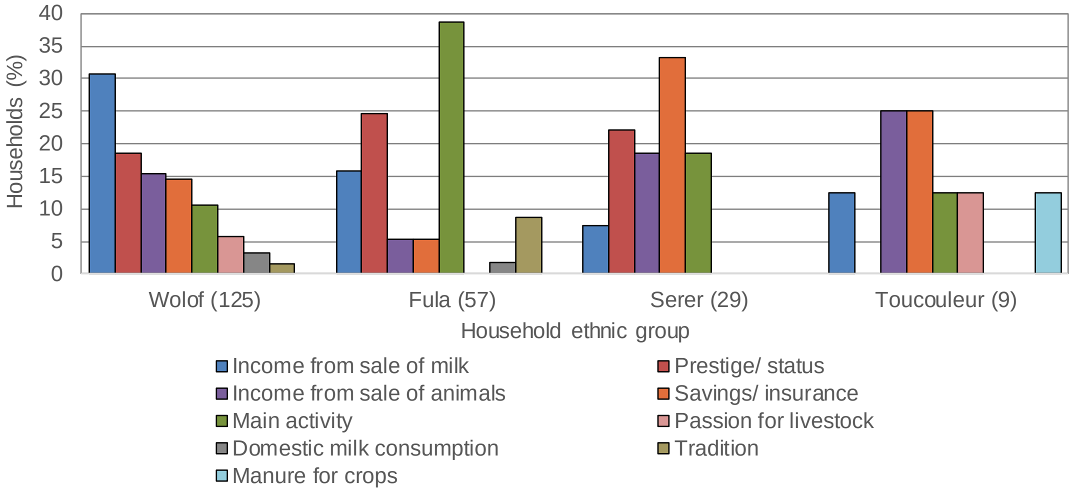

Figure 2.10. Households' primary reason for rearing cattle shown for the different ethnic groups in the population. The number in brackets indicates the total number of households in each ethnic group. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

Motivating factors for rearing cattle also varied between households in different income brackets. As Figure 2.11. suggests those households in lower income brackets have more reliance on cattle as their main activity; whilst those in higher income brackets have more varied values of cattle, with prestige/status and the income from milk and animal sales being more important.

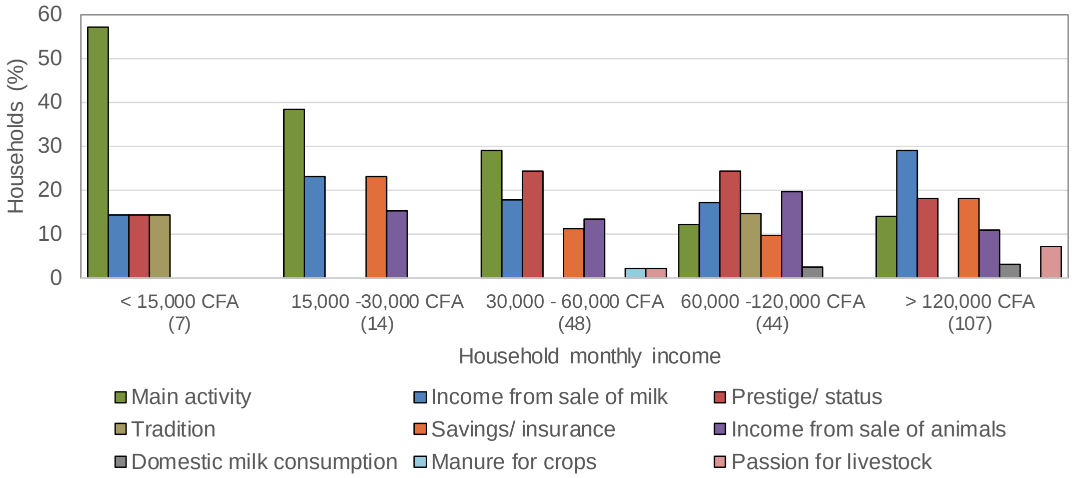

Figure 2.11. Households' primary reason for rearing cattle shown for the different household income brackets. Income is in Central African Francs (CFA), with an approximate exchange rate of 1 CFA = 0.0016 USD. The number in brackets indicates the total number of households in each income bracket. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.5.2. The introduction of non-indigenous cattle breeds

Responses from the household head suggest that the introduction of non-indigenous cattle breeds to the study households generally took place in the decade following the turn of the millennium (Figure 2.12.). This would indicate that the majority of study households have been managing non-indigenous cattle breeds for up to twenty years.

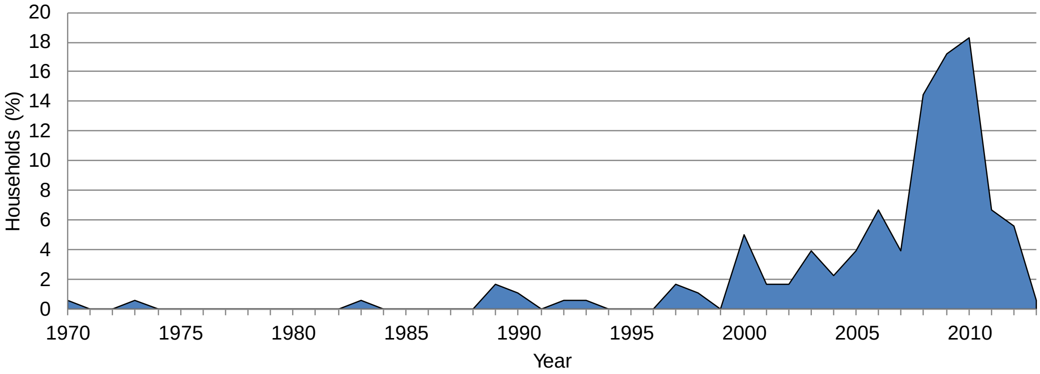

Figure 2.12. Timeline of households' first use of non-indigenous cattle breeds. Derived from information gathered through SDG baseline survey questions answered by the household head (in 2013).

It was apparent that other than farmers using their own initiative (37% of households) it was neighbouring livestock keepers (30% of households) and practicing vets (19% of households) which were responsible for recommending the rearing of non-indigenous cattle breeds. The significance of neighbour to neighbour information transfer and extension services (it is suspected to be largely provided by vets in this instance) is common in SSA (Roschinsky *et al.*, 2015). Following such recommendations, the introduction of non-indigenous cattle breeds is largely through the purchase of non-indigenous or crossbreed animals (41% of households); or through use of one of the Senegalese government implemented artificial insemination (AI) programmes (38% of the households), of which there have been three (1999, 2001, and 2004) (Seck and Fadiga, 2016). Non-government organisations (NGOs) played a very minor role in encouraging or supplying non-indigenous cattle breeds and for the study households (1% of households).

2.5.3. Constraints to cattle rearing

The survey questions for the SDG project revealed that the key constraint to the rearing of cattle, as identified by 70% of study households, was cattle feed limitations. This related to both high costs and problems with accessing good quality feed (Figure 2.13.). Nutritional limitations to cattle systems in SSA is a consistent theme (A. N. N. Hristov *et al.*, 2013; Opio *et al.*, 2013). The theft of animals, reported as the key constraint by 9% of households, has also been recognised as a constraint to systems in other studies in Senegal and West Africa (Bouyer *et al.*, 2015; Mertz *et al.*, 2010).

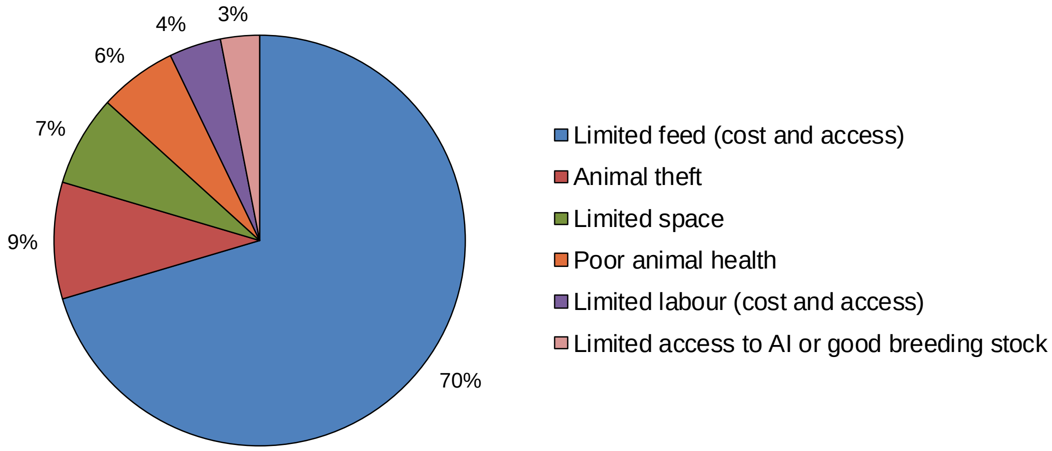

Figure 2.13. Households' (%) key constraints to the rearing of cattle. Information gathered through SDG baseline survey questions answered by the household head (in 2013).

2.5.4. Cattle system rations

Rations used by study households in each defined cattle production system (Table 2.2.) were derived from cattle feeding information gathered through the SDG surveys. These consisted of 14 cycles of household visits, between May 2013 and April 2015. There was a high level of variation in ration compositions (in both material contents and ration proportions), this was standardised to the rations shown in Table 2.3. (standardisation is further discussed in Appendix A). Rations defined here are an annual average; rations with seasonal variation (wet and dry) can be seen in the Appendix A.

Table 2.3. Feed ration components (%) for the seven defined production systems. The ingredients of purchased compound feed are included within the main ration components, and the purchased compound feed proportion of the total ration (% of total ration) is shown in the last row. Derived from information gathered as part of the SDG surveys (2013- 2015).

Feed component	**IZ**		**IZ x GZ**		**IZ x BT**		**BT**
	+	**++**	**+**	**++**	**++**	**+++**	**++++**
Maize grain	0.6	2.0	1.9	1.8	2.2	3.3	11.4
Millet stover	10.1	10.0	11.6	10.9	7.3	3.1	15.4
Brans	4.9	11.0	8.3	6.8	9.2	13.4	24.9
Groundnut cake	5.0	7.2	5.4	5.9	10.4	13.1	17.3
Groundnut shells	0.4	1.1	0.9	1.0	1.0	1.8	3.5
Natural pasture (grazed)	74.1	55.6	62.3	63.5	51.6	34.2	7.8
Natural pasture (cut and carry)	1.0	3.6	1.2	1.6	3.2	5.9	2.7
Natural pasture (hay)	3.9	9.5	8.5	8.5	14.9	25.2	17.0
Purchased compound feed	3.6	9.1	7.7	8.1	8.9	16.5	32.0

See Table 2.1. and Table 2.2. for details of breed type (e.g. IZ x GZ) and management level (e.g. +++)

2.5.5. Cattle system production parameters

Key production parameters for the each defined cattle production system (Table 2.2.) are shown in Table 2.4.; further system parameters are presented in Appendix B. The animal weights presented here represent a snapshot in the likely annual variation in body weight of cattle, as environmental conditions and feed availability vary with the seasons (Ayantunde *et al.*, 2008; Powell *et al.*, 1996). Milk offtake will also vary seasonally, so the offtake presented in Table 2.4. is an annual average.

Table 2.4. Key production parameters for each defined cattle production system. Derived from information gathered through SDG survey (2013 - 2015).

Parameter	**Unit**	**IZ**		**IZ x GZ**		**IZ x BT**		**BT**
		+	**++**	**+**	**++**	**++**	**+++**	**++++**
Mature cow weight	kg	294	317	302	309	333	414	433
Mature bull weight	kg	383	413	393	403	434	539	564
Calf birth weight	kg	21	22	21	22	23	29	30
Milk offtake	kg/year/ lactating cow	323	877	411	989	937	2032	2197
Age at first calving	years	4.3	3.8	3.7	3.7	3.5	3.5	3.3

See Table 2.1. and Table 2.2. for details of breed type (e.g. IZ x GZ) and management level (e.g. +++)

Evidently the information gathered as part of the SDG project (Box 1.2.) and explored in this chapter, gave a detailed understanding of the study production systems. The fieldwork presented in Chapter three gives further context to these specific systems.

CHAPTER THREE

SENEGAL FIELDWORK

3.1. Objectives of the fieldwork

Chapter one explained the growing demand for cattle produce in SSA (driven by increasing urbanisation and incomes, and growing populations), and the suggested efforts by the Senegalese government to increase domestic production (Seck and Fadiga, 2014). However, the extent to which livestock keepers are willing and able to engage in productivity improving activities is not clear. Therefore, to inform modelling and improve any suggestions or conclusions made from results, fieldwork was carried out in April to May 2016 to meet the following objectives:

1) Investigate livestock keepers' attitudes to productivity improvement.
2) Identify potential barriers that may restrict uptake of mitigation measures by livestock keepers.
3) Observe which mitigation measures livestock keepers propose themselves.
4) Improve the understanding of the current situation for livestock keepers.
5) Gather information to strengthen the accuracy of modelling.

3.2. Fieldwork methods

Focus group discussions (FGD) with study livestock keepers and semi-structured interviews with other livestock industry stakeholders were employed.

3.2.1. Focus group discussions with livestock keepers

FGD templates were initially drafted by the author, then edited and translated (into French and Wolof[4]) with the assistance of employed facilitators and enumerators. The translation process provided an opportunity to explain what was required from the FGDs (allowing facilitators freedom to effectively gather information) and to receive guidance as to what study livestock keepers would understand and relate to. The FGD templates were designed to address the fieldwork objectives using both open questions, to understand where livestock keepers' attentions and perceptions lie; and more specific questions to address the viability of specific productivity improving measures. The FGD templates can be viewed in Appendix C. Following

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[4] The Wolof language is a lingua franca in both Senegal and The Gambia (Kane, 2009).

drafting, the templates were piloted with a group of local livestock keepers (not included in the study) to identify any problems with design or facilitation (Figure 3.1.). This allowed revision before proceeding to the study livestock keepers.

Figure 3.1. Left: Piloting the focus group discussion templates with non-study livestock keepers. Right: Study livestock keeper meeting, where a focus group discussion was conducted.

Participants of the FGDs were recruited through their previous involvement in ILRI's SDG project (Box 1.2.). The SDG project purposefully selected cattle keeping households to include examples of improved cattle breeds (non-indigenous) (Marshall *et al.*, 2014; Tebug *et al.*, 2016), and as such may not be fully representative of the views and opinions of the wider livestock keeper population (who may rely more heavily on indigenous breeds).

The FGDs were carried out at eight meetings of households in May 2016 (Figure 3.1.; Table 3.1.). Attendees included 88 women and 166 men from the Thiès and Mbaké regions (Figure 2.1.). Due to limited access to facilitators and enumerators each FGD had an average of 20 participants. In an attempt to avoid possible dominance of certain individuals in such large groups (as suggested by past authors (Oya, 2001; Reed and Hickey, 2016)), attendees were divided into low and high wealth groups. To avoid public displays of wealth, and herd size being deemed unsuitable as a proxy, the last sale of milk was used to make this categorisation. Increasing time periods were used as categories until the total attendees at the meeting were divided into approximate halves. This was based on an assumption that as meetings were being held in the dry season, it would be wealthier households which were more likely to be able to afford inputs and management to still be producing and selling milk.

The facilitators and enumerators had an existing relationship with the livestock keepers through previously working on the SDG project. They were also able to conduct the FGDs in Wolof and record results in French. To avoid bias facilitators and enumerators were switched between high and low wealth groups at each meeting. Transcripts were translated into English, and then manually coded to identify common themes appearing in answers and comments.

Table 3.1. Focus group discussion details and reference codes for in text information

Date	Site	Wealth group	Ref[1]	Men	Women
3rd May	Touba Toul, Thiès	High	Tou.H	6	7
3rd May	Touba Toul, Thiès	Low	Tou.L	14	12
4th May	Thies, Thiès	High	Thi.H	16	0
4th May	Thies, Thiès	Low	Thi.L	3	2
10th May	Kael, Diourbel	High	Kae.H	11	10
10th May	Kael, Diourbel	Low	Kae.L	15	15
11th May	Mbacke, Diourbel	High	Mba.H	10	15
11th May	Mbacke, Diourbel	Low	Mba.L	32	4
12th May	Missira, Diourbel	High	Mis.H	15	15
12th May	Missira, Diourbel	Low	Mis.L	16	3
15th May	Tivouane, Thiès	One group[2]	Tiv.O	10	1
16th May	Pire, Thiès	High	Pir.H	8	1
16th May	Pire, Thiès	Low	Pir.L	10	3

[1] Reference used to indicate the focus group discussion relevant to specific information referenced or quoted in the text

[2] Due to limited availability of facilitators and enumerators, and the small group size, there was only one group at Tivouane

3.2.2. Semi-structured interviews with livestock industry stakeholders

The purpose of the semi-structured interviews with stakeholders from the local livestock industry was to understand their opinion on local livestock keepers' attitudes and challenges to improving the productivity of their animals. Interviewees included a veterinarian practicing in the study region, a nutrition scientist for a Dakar based feed merchant (who produce the compound feed study livestock keepers have access to through traders) (Figure 3.2.), an individual farmer (who as one of the study facilitators was accessible for more detailed conversation), and livestock researchers based in Senegal (Table 3.2.). The semi-structured interviews aimed to:

- Improve the understanding of local cattle production systems and the likely future of the study systems.
- Discuss specific productivity improving measures; to further understand their viability for application to study systems.
- Acquire further information relevant to the specialisms of different stakeholders. For instance the veterinarian was asked about animal health challenges and the cost of animal health treatments; whilst the feed nutrition scientist was asked about the use of concentrate compound feeds and feed costs.

Figure 3.2. Left: NMA Sanders feed mill, Dakar. Right: Compound feed available to study farmers from local traders, produced by various feed companies.

Table 3.2. Details of livestock system stakeholders from whom information was gathered through semi-structured interviews and broader discussions.

Name	Role	Location and date of meeting
Dr Meissa N'Diaye	Vet practicing in the Thies region	ILRI project office (Dakar) 7.5.16
Dr Cheikh Alioune Konate	Nutrition scientist NMA Sanders[1] (Feed producer)	NMA office and mill (Dakar) 6.5.16
Dr Christian Corniaux	CIRAD[2] Agronomist and zoo-technician. West Africa specialism	CIRAD office (Dakar) 27.4.16
Dr Philippe Lecomte	CIRAD Livestock researcher	CIRAD office (Dakar) 27.4.16
Yakhya Elhadji Thior	EISMV[3] Dakar - PhD student researching local feed materials	ILRI project office (Dakar) 7.5.16
Professor Ayao Missohou	EISMV Dakar - Head of Department of Biological Sciences and Animal Production. Research interest in the area of livestock breeding and husbandry	Professor Missohou had a role in the SDG project and supported the author during fieldwork allowing extensive discussion
Dr Stanly Fon Tebug	ILRI[4] - Animal scientist with a veterinary background. Experience working with smallholder livestock producers in developing countries with special interest in dairy production. Based in Senegal co-ordinating local field activities.	Dr Tebug had a role in the SDG project and supported the author during fieldwork allowing extensive discussion

[1] NMA Sanders: a Senegalese agri-food company

[2] CIRAD: the French agricultural research and international cooperation organization working for the sustainable development of tropical and Mediterranean regions.

[3] EISMV: the Interstate School of Veterinary Science and Medicine, Cheikh Anta Diop University of Dakar

[4] ILRI: the International Livestock Research Institute

3.3. Results and key findings from the fieldwork

Fieldwork findings are presented below by theme or question. Direct transcript quotes are used where it is felt it represented an interesting view, opinion or situation relevant to the wider study.

3.3.1. Livestock keepers' attitudes towards improving productivity

During the FGDs study livestock keepers were unanimous in agreeing it was very important for them to improve the productivity of their systems. The majority also affirmed that with more productive individual animals, they would reduce their herd sizes, reducing associated GHG emissions. There were a minority of individuals in both low and high wealth groups that disagreed, and would not reduce their herd sizes if their animals were more productive. This minority was greater in the low wealth groups (Figure 3.3.) Although efforts were made to reduce social pressures by splitting into high and low wealth groups, it is possible that responses were influenced by social hierarchy or dominance within the groups.

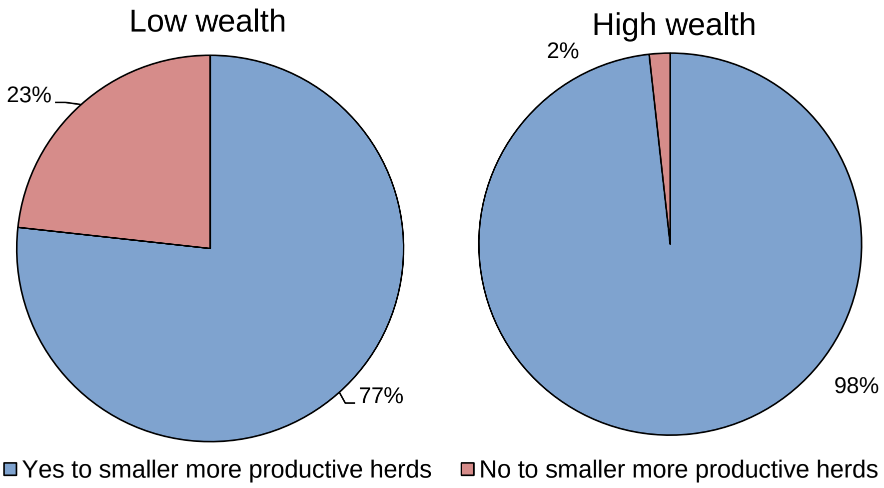

Figure 3.3. The proportions of livestock keepers' responses to the question: *"Would you be interested in producing the same output with fewer animals?"* shown by wealth group.

Livestock keepers that demonstrated enthusiasm for improving the productivity of their animals, and reducing their herd sizes, suggested both that smaller herds required fewer inputs and therefore lower costs, *"…less animals require less investment"* (Thi.H); and that with smaller herds more could be invested in each animal, *"…investing more in less animals"* (Tou.L). There was also reference to smaller herds being easier to manage effectively, *"…managing a smaller herd is easier"* (Tou.L) and in particular *"…easier management of their nutrition"* (Tou.L).

Conversely, the reasons why some livestock keepers were not intent on reducing their herd sizes could be associated with the varying ways cattle are valued in SSA. There was agreement that increasing productivity was beneficial, participants *"do agree that more milk from less animals is good, but there are other needs for cattle"* (Thi.H). They emphasised that cattle fulfil other requirements, *"choices are not based solely on milk production, for example the sale of animals to cover certain expenses is important"* (Tiv.O). There was also reference to the ceremonial or social function of cattle, as two participants explained:

> *"…cattle are important for ceremonies, a cow is slaughtered, if they have less cows this makes a big impact on their herds, with many cows this isn't a problem"* (Thi.H)
>
> *"…more animals meaning more consideration and respect"* (Kae.L)

Another participant described how indigenous cattle breeds may be less productive, but are resilient in a high risk environment. Such a production strategy is logical in a scenario where support and investment is limited.

> *"…with a high number of local cattle breeds, feeding isn't that important and I still get milk"* (Tiv.O).

3.3.2. Livestock keepers proceeding to improve productivity

Previous studies have shown that livestock keepers are likely to be more responsive to productivity improving measures that they already understand and value (Adesina and Chianu, 2002; Ndjeunga and Bantilan, 2005). Livestock keepers in developing regions often have valuable indigenous knowledge, as well as varied social and cultural features, these must be considered when planning improvements (Gning, 2004; Nyong *et al.*, 2007).

When productivity improvements were discussed, livestock keepers from both low and high wealth groups were aware of a range of potential options. Broad themes included improving: housing, feed quality and quantity, health status, breeds and water access. The study livestock keepers' prior involvement in the SDG project, and the education and training this provided, could explain their appreciation of this extensive variety of interventions. Their level of knowledge and comments could be different from the wider population.

Some participants went into further detail and proposed more specific ways to improve productivity. These included options to improve disease treatments; as well as better and more accessible training in animal health, milk preservation, and forage conservation and processing. Low and high wealth groups showed no significant difference in referencing specific options to improve productivity. FGDs suggested that a positive response to productivity improving interventions can be expected amongst study livestock keepers, particularly to those measures they already value. There is also a desire from livestock keepers for further education and capacity building to improve the execution of such interventions.

3.3.3. Key barriers to productivity improvements

Livestock keepers were asked about barriers preventing productivity improvement. Both low and high wealth groups cited an overarching lack of financial resource as the main barrier. This included reference to funds required to improve cattle housing, afford AI, effectively apply health management, buy improved breeds and afford adequate feed. The next most frequently cited barrier was a lack of information and training, this was mentioned by a greater proportion of high wealth, than low wealth groups.

Other commonly cited barriers, generally experienced equally by low and high wealth groups, included: limited access to veterinarians (more frequently mentioned by low wealth groups), low pasture quality (Figure 3.4.), challenges in securing access to adequate pasture, the access to and high cost of desirable breeds and large herd sizes.

Other barriers mentioned by a low number of groups included: transhumance and the limitations this imposes on management, the high cost and poor results of AI, and competition for land between livestock keepers and crop farmers. FGDs suggest that improving affordability and accessibility of resources could increase productivity improvements; however other barriers could then become more apparent and would need to be overcome for improvement to be realised.

Figure 3.4. Cattle being herded through poor quality pasture. (Photo credit: ILRI)

3.3.4. Livestock keepers' attitudes towards nutritional improvements

The FGDs further investigated attitudes to more specific measures by encouraging discussion and comment, these are summarised in Table 3.3.; the following sections discuss the main barriers identified.

Table 3.3. Summary of responses and barriers mentioned to the proposal of specific feed related productivity improving measures. Both improvements to the existing and increased use of measures were considered.

Measure	**Responses**	**Potential barriers**	
		Commonly mentioned[1]	**Other**
Concentrate feeds	All positive	• Financial resource • Cost • Access	• Low rainfall/poor harvest • Materials/equipment • Space • Access to credit • Labour
Pasture improvement	Majority positive Minority negative – *cattle housed so grazing not important*	• Land competition • Cattle damage • Financial resource • Land rights • Bush fires • State support • Seed quality	• Low rainfall/poor harvest • Soil degradation
Conserved feed	All groups positive	• Time • Materials or equipment • Storage facilities • Financial resource • Knowledge/training • Large herd size • Labour • Pasture quality	• Access to pasture • Bush fires • Transhumance
Forage treatment and processing	Majority positive Minority negative – *lack of technical knowledge*	• Knowledge/training • Materials/equipment • Time • Labour • Large herd size • Financial resource	• Access to resources • Transhumance

[1] Barriers listed in order of regularity of reference by FGD groups

3.3.4.1. Financial resource

Despite finance/credit providers existing in Senegal, with the purpose of modernising livestock production (e.g. FONSTAB[5]), the lack of financial resource was cited as a barrier for all the productivity improvement measures discussed. As described by one participant:

> *"…the low income level of farmers does not allow them to buy feed to the quality and quantity required"* (Mba.L)

As anticipated low wealth groups expressed a lack of financial resource as a barrier more often than high wealth groups.

3.3.4.2. High cost of resources

The high cost of resources (most commonly mentioned was concentrate feeds) was frequently referenced as a barrier to increased application. High wealth groups mentioned the high cost of resources, as opposed to the lack of financial resource, to a greater extent than low wealth groups.

3.3.4.3. Limited access to resources

The lack of access to resources was frequently referenced as a barrier to increased application for all productivity improvement measures suggested to livestock keepers. For instance *"availability and proximity of feed, at times is a problem"* (Thi.H); this was experienced to a greater extent in the dry season. For pasture improvement there was a lack of access to seed. Whereas for forage conservation, treatment and processing, it was a lack of access to equipment to carry out the processes which was limiting. Poor access to resources was felt equally amongst households from both Thiès and Mbaké regions.

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[5] http://www.ladoum.sn/generalites/fonstab-un-credit-adapte-a-l-elevage.html

3.3.4.4. Land availability

Responses from livestock keepers suggested that the improvement and effective utilisation of pastures was limited by land availability, *"there are many new industries in the area which limits grazing land space"* (Thi.L). Competition between pastoralists and arable farmers was the most commonly cited barrier (62% of groups), this is a common scenario in SSA (Oosting *et al.*, 2014). There was a feeling amongst study livestock keepers that the State support favours arable agriculture over livestock with regards to space. Reviews have suggested this is true, particularly with political weight from large mono-crop producers and a historic emphasis on crop production (Gning, 2004).

3.3.4.5. Communally accessed land

Comments suggest that the communal nature of pasture use is a constraint to individuals attempting to improve areas of pasture.

> *"…there are misunderstandings between livestock keepers, so they struggle to improve communal pastures"* (Pir.L)
>
> *"…animals do not have a fixed route during transhumance, so other cattle can destroy pasture"* (Tou.L)

The incentives to improve pastures, or their utilisation, are limited when other livestock keepers can exploit efforts or cattle herding can destroy improved pastures. For this reason, the improvement of natural pastures is an uncommon practice (Lo, M. personal communication, 29.4.16).

3.3.4.6. Time constraints

Limited time was a key barrier to the increased conservation of forages and their treatment and processing. One participant described:

> *"…the time for cultivation and preparation of forages coincides with the harvest season"* (Mba.L)

The high seasonality of vegetation growth means labour is limited due to the harvest of food crops for human consumption.

3.3.4.7. Specific system characteristics

The act of transhumance, when cattle are herded to access pasture resources, limits the feasibility of increased use of conserved feeds, or the processing and treatment of forages before feeding. Large herd sizes were also cited as a challenge to the use of feed conservation techniques, and forage processing and treatment; *"because there are a lot of animals to feed"* (Kae.H). There were also comments concerning the quality of pastures limiting the feasibility and effectiveness of forage conservation (e.g. silage making). This demonstrates the importance of development being progressed as packages of measures, rather than standalone acts (e.g. pasture may need improvement before forage conservation would be beneficial).

3.3.4.8. Knowledge and the need for training

The lack of understanding of how to implement measures, and the need for relevant training was apparent as a limitation for feed conservation, processing and forage treatments. The benefits of investing in improved cattle breeds and appropriate feeding was understood by all groups, however as mentioned this could be due to their prior involvement in the SDG project (Figure 3.5.).

Figure 3.5. The SDG project collected data from the production systems over two years, through which livestock keepers also received education and information concerning productivity improvement options. (Photo credit: ILRI)

3.3.5. Agricultural productivity through livestock-crop interaction

Livestock-crop interactions are common amongst smallholder systems in SSA, with manure providing fertiliser, and livestock providing draught power and a purpose for crop residues (Herrero *et al.*, 2009). This link was recognised by study livestock keepers, with all groups unanimously agreeing there is a close link between crop and cattle productivity. Section 2.4.2 suggests that at least a third of the study livestock keepers manage agro-pastoral systems. Groups commented on the use of crop residues to feed cattle, and the reciprocal use of manure to fertilise crop growth. There was also mention of the insurance cattle provided, should harvests fail; and the importance of draught power. All groups agreed they would like to improve their crop yields to help improve cattle productivity. When asked how they would do this, common responses included: the increased use of manure as crop fertiliser, increased labour dedicated to crops, the sale of livestock to access resources such as good seed, and more draught power. These results suggest that within these particular systems the link between livestock and cropping could be enhanced and that this is generally understood by livestock keepers.

When asked about the barriers to making these improvements the responses were varied with no overly common themes. Transport issues, in particular a *"lack of means to transport manure"* (Pir.H) to use for fertiliser was most commonly referenced. Space problems were also mentioned, with *"no space to store manure"* (Tou.H); as were the broad themes of a lack of funds and access to resources. One barrier widely discussed concerned security, one participant explained the challenge:

> *"…cattle theft makes it difficult to keep animals on crop fields, meaning that manure has to be carried to crop farms"* (Pir.L)

3.3.6. Animal health

Health challenges represent a substantial burden to cattle productivity in developing regions (Perry and Grace, 2009; Perry and Sones, 2007). All groups recognised the benefit improving animal health could bring to productivity. Both low and high wealth groups cited Pasteurellosis, Foot and Mouth Disease (FMD) and Trypanosomiasis (Tryps) as the three most significant health challenges. An interview with a local practicing veterinarian, suggested that the prevalence and impact of Pasteurellosis might be less than that reported by households:

> *"Pasteurellosis could be commonly misdiagnosed by the farmer, and could be symptoms of something else"* (Dr N'Diaye, personal communication, 7.5.16).

From the veterinarian's perspective the three most problematic conditions for cattle productivity were Lumpy Skin Disease (LSD), FMD and Tryps (Dr N'Diaye, personal communication, 7.5.16).

Difficulty in accessing veterinarians was the main barrier referenced by livestock keepers. The practicing veterinarian explained how veterinarians are limited and expensive for livestock keepers:

> *"It is true there are not really enough veterinarians for the number of farmers in the region, but cost is also prohibitive. The government used to provide veterinarian services for free, but this has now stopped, with increasing budget cuts and privatisation. There are private veterinarian services, but the farmers are not used to having to pay for the service."* (Dr N'Diaye, personal communication, 7.5.16).

The veterinarian also commented that the uptake of specific animal health interventions depends largely on the cost to livestock keepers:

> *"The uptake by farmers to make change depends largely on cost, for example the foot and mouth vaccines are expensive, if they have to sell a cow to be able to afford the vaccine for other cows, they are unlikely to do this, it is hard to justify. Whereas the lumpy skin vaccine is much cheaper, so they are more likely to uptake this. To treat trypanosomiasis is fairly cheap, so it's common for farmers to use trypanocides"* (Dr N'Diaye, personal communication, 7.5.16).

The trade-offs and costs of improving animal health that livestock keepers experience appear to be a key barrier to productivity improvements. It has also been suggested that health conditions commonly go unnoticed, untreated and unreported (Tebug *et al.*, 2015).

3.3.7. Animal breeding

The genetic selection and crossbreeding of cattle can improve production potential (Chagunda *et al.*, 2015; Marshall *et al.*, 2016b), consequently there have been efforts in SSA to improve the resilient indigenous breeds, with the introduction of exotic breeds, with higher yields (Marshall *et al.*, 2014; Menjo *et al.*, 2009; Somda *et al.*, 2005). When breeding goals were discussed with study livestock keepers there was emphasis on both increasing milk production and increasing body sizes, illustrating the multi-functionality of the cattle. A challenge when crossbreeding, that became apparent during FGDs, was the breeding of a Zebu dam with an exotic (Bos Taurus) sire; the increased calf size can cause damage or death to the dam ,*"there is a high calf mortality and female mortality with calving, particularly when cross breeding with larger breeds"* (Tou.L). For this reason, livestock keepers also looked to *"pick breeds that calve easily"* (Tou.L) when crossbreeding.

AI and accessing desirable animals were the referenced methods to improve herd characteristics. The main barriers to using these to make improvements was limited financial resource and difficulty accessing private and public/government AI services, expressed equally by low and high wealth groups. The lack of information regarding breeding options was also mentioned by both low and high wealth groups. Less commonly referenced was the low conception rate from AI, *"we stopped inseminating because the results were not encouraging"* (Tou.L).

AI was discussed with the local practicing veterinarian, who commented that the government offer annual AI programmes to improve the genetics of herds, however these are thinly spread across regions and declining with budget cuts. Past authors have suggested that the government AI is not fairly distributed (Gning, 2004). Private AI is available, but the cost and poor results make this unattractive to the livestock keepers.

3.3.8. Other challenges facing study livestock keepers

To conclude FGDs study livestock keepers were asked if anything had not been covered in the discussions. All groups commented that there was a significant problem with the theft of cattle; and that this needed to be more tightly controlled by *"identifying thieves at the local market and reinforcing police officers"* (Mis.L). The risk of cattle theft can be considered a strong disincentive for any improvements to cattle productivity.

A minority of groups mentioned seasonal oversupply of milk:

> *"Pire region produces a lot of milk, the price for milk is low. This is noticed most in the wet season when the market is flooded and we see a price crash"* (Pir.L).

A milk excess in the wet season, with a deficit in the dry season is also mentioned in the literature (Knips, 2006). Incentives to improve productivity may therefore be seasonal, with the challenge being to maintain productivity throughout the year.

Both FGDs and interviews suggested that there was an element of dissatisfaction with State support amongst livestock keepers, with mention of State imposed constraints. An example was given concerning the *Acacia albida* trees, which remain green all year and provide a vital last resort feed resource for livestock keepers (Figure 3.6.). However, the act of cutting the branches to let the cattle feed is now controlled under conservation policies (Tebug, S., personal communication, 2016).

Figure 3.6. Green vegetation becomes limited as the dry season progresses.

3.3.9. Future prospects for study systems based on fieldwork

Senegal has seen the establishment of more intensive cattle systems around urban areas, and with greater investment and inputs a constant reliable supply of product is guaranteed (Knips, 2006; Yameogo *et al.*, 2008). Stakeholders were asked what they thought the future was for the low input and semi-intensified cattle systems investigated in this study. There was a common understanding that the emergence of more intensive systems was likely to continue to meet growing urban demands, and that study systems were unlikely to be competitive in the same markets. The practicing veterinarian clarified that the number of traditional herds was declining:

> *"I am already seeing a decline in traditional smallholder systems, these are being replaced by more productive urban higher systems"*
>
> (N'Diaye, 2016, personal communication, 7 May).

The feed nutritionist commented on the general trend of increasing intensification in the sector, and potential issues with the traditions of study systems that could limit them in the future:

> *"…there is a move towards more intensive systems. Demand for milk is increasing, so large processors are growing to meet this. They want a consistent supply so they can guarantee production. Smallholders cannot guarantee this so risk missing this market. The future is with larger groups as it is a good investment. There is a cultural challenge with the smallholders, who want to keep taking cattle out to graze poor dry pastures. They need to realise that they can improve productivity by keeping them indoors and feeding higher quality feeds"*
>
> (Konate, 2016, personal communication, 6 May).

Following this suggestion that cultural norms and tradition could limit productivity improvements and potential for these systems, the issue was discussed with Dr Tebug, who had worked closely with the study livestock keepers during the SDG project. It was confirmed that sometimes tradition can be limiting:

> *"…farmers take time to change (maybe through generations). They discuss and say things are a good idea, but how many actually practice and improve is questionable"* (Tebug S. 2016, personal communication, 6 May).

The lack of consistency of supply and competition with cheap imported milk powder (Gning, 2004) make low input systems unattractive to commercial customers (Knips, 2006). The intensive systems are better equipped to meet growing demands. However, efforts to increase the productivity of study systems are still relevant, firstly to assist in local food security. Secondly, there are examples of commercial viability of smallholder systems through a more collective approach to the market. Nestlé collected milk from pastoral regions through village cooling tanks and effective transport to markets in urban areas, this ended in 2003, largely due to the seasonality of supply limiting Nestlé's return on investment (Knips, 2006). Laitière du Berger (Parisse, 2012), and other cooperatives and family businesses, still source rural milk, process and sell to urban markets; they focus on the branding of local produce as a higher quality than imports and effective distribution (Gning, 2004; Knips, 2006). The Senegalese Government has reportedly been keen to promote these small scale dairy units, and reduce reliance on milk imports (Knips, 2006). Smallholder informal dairying is a mainstay of milk production in other developing regions (e.g. India (80% of the sector is dominated by informal producers and East Africa) (Bebe *et al.*, 2002; Lindahl *et al.*, 2017; McDermott *et al.*, 2010).

3.3.10. Summary of the main findings from fieldwork

Study livestock keepers showed an eagerness and desire to improve the productivity of their herds; with the majority agreeing they would be happy to have fewer, more productive, animals.

- Open discussions with study livestock keepers suggest that they are aware of what actions they could take to improve their herd productivity. This is likely an example of the success of the education provided by the SDG project. The wider livestock keeper population would need to be sampled through further FGDs to confirm patterns to a broader scale.
- Study livestock keepers suggested that barriers to making productivity improvements included:
  - A lack of financial resource;
  - The high cost and limited access of key resources;
  - Land use competition and conflict;
  - Time and labour constraints;
  - A need for training and information concerning specific options for productivity improvements;
- The complexity of barriers mentioned, by FGDs, suggest that to realise productivity improvements multiple barriers may need to be overcome. It was also apparent that the removal of primary barriers may reveal further complications that need addressing.
- It appears likely that the low input and semi-intensified systems in this study will face increasing competition from more intensive developed systems for the growing urban milk market. However, productivity improvements are still warranted to improve local/rural food security and livelihoods, and to fulfil rural markets. The increased formation of co-operatives appears to be the best option for these livestock keepers' futures.

CHAPTER FOUR

MITIGATION MEASURE SHORTLISTING

4.1. Considering mitigation measures

In this context mitigation is defined as an intervention to reduce the GHG emissions from a production process (including both reduced emissions sources and increased emissions sinks) (Muldowney *et al.*, 2013). In the context of SSA's increasing population and demand for food from livestock (specifically cattle) (Chapter one), it can be assumed that production will continue to increase (Herrero *et al.*, 2008). Therefore, the supply must be considered. Mitigation is likely to be achieved through improving the efficiency of production, to reduce the Ei of produce, whilst production inevitably increases. This has been recognised by livestock researchers and there have been several comprehensive reviews of the options to reduce Ei by increasing productivity (Gerber *et al.*, 2013a; A. N. Hristov *et al.*, 2013; A. N. N. Hristov *et al.*, 2013). Improvements to both animal nutrition and health have been suggested as key avenues for improved productivity and reduced Ei for SSA smallholder systems (A. N. N. Hristov *et al.*, 2013).

4.1.1. Animal feed and nutrition

CH_4 from ruminal (enteric) fermentation is a key emissions category for cattle systems, contributing to a large proportion of total sector emissions (Figure 1.1.). This can be directly reduced by improving the quality of cattle feed, and is often considered a 'win-win'; as reducing emitted CH_4 represents a reduced loss of dietary energy, through an improved feed efficiency and equates to a reduction in costs (Beauchemin *et al.*, 2008) (Box 4.1.). This is particularly pertinent in developing nations where nutrition is known to often limit productivity (Sumberg, 2002; Thornton, 2010), in these scenarios 'win-win' options are likely to be key in engaging livestock keepers (Reynolds *et al.*, 2011).

Box 4.1. Reducing enteric methane emissions from cattle

Methane (CH_4) is a major by-product of carbohydrate fermentation by methanogenic archaea bacteria, in the rumen of cattle. The majority is produced under anaerobic conditions in the reticulo-rumen. Whilst the bacterial activity is beneficial to cattle, improving the breakdown of organic matter; the production of CH_4 has no direct benefit and represents a loss of dietary energy (Boadi *et al.*, 2004).

During the conversion of feed material into CH_4, the primary step is the hydrolysis of proteins, starch and plant cell wall polymers into amino acids and sugars by digestive micro-organisms. These are then fermented to volatile fatty acids (VFA) (acetate (1), propionate (2) and butyrate (3)), hydrogen (H_2) and carbon dioxide (CO_2) (Boadi *et al.*, 2004).

$$C_6H_{12}O_6\ (sugar) + 2H_2O\ (water) = 2C_2H_4O_2 (acetate) +\ 2CO_2 + 8H \qquad (1)$$

$$C_6H_{12}O_6\ (sugar)\ + 4H\ = 2C_3H_6O_2\ (propionate) + 2H_2O \qquad (2)$$

$$C_6H_{12}O_6\ (sugar)\ =\ C_4H_8O_2\ (butyrate) + 2CO_2\ + 4H \qquad (3)$$

The host cow absorbs and utilises the VFAs; whilst the H_2 produced (predominantly by the same organisms that produce the acetate) does not accumulate but is used by methanogenic bacteria to produce energy, releasing CH_4 (4).

$$CO_2\ +\ 8H\ = CH_4\ (methane) + 2H_2O \qquad (4)$$

Evidently, acetate and butyrate production results in CH_4 production; whilst propionate production competes with methanogens for use of the H_2, reducing CH_4 production. When propionate production is increased, acetate and butyrate production are reduced. Nutritional measures to reduce the production of enteric CH_4 are based on the following approaches (Knapp *et al.*, 2014):

1) Selection of feed ingredients (based on digestibility and chemical composition) to alter the pattern of VFA production, with an aim to enhance propionate production and reduce H_2 converted to CH_4. Feeds rich in starch will favour propionate production, whilst those roughage based will favour acetate production (Johnson and Johnson, 1995).
2) Increasing the rate of passage of feed through the rumen, thus altering the rumen microbial populations and VFA production patterns; as well as promoting digestion beyond the rumen, in the intestine.
3) Improving the quality of feed ingredients (increasing energy density and/or digestibility), increases the proportion of gross energy consumed used for production, diluting the CH_4 associated with maintenance energy requirements (i.e. increased feed efficiency) (Knapp *et al.*, 2014).

In addition there are also rumen modifiers, specific substances added to feed rations that inhibit methanogenic bacteria and methanogenesis. These include ‘chemical inhibitors, organic acids, and plant secondary compounds’ (Knapp *et al.*, 2014).

Measures could include the effective supplementation of high forage/roughage diets (e.g. grass, hay, straw and whole crops) with concentrate feeds (e.g. high energy/nutrient grains and compound feeds); improving both feed digestibility and energy density and increasing feed use efficiency. However, in developing regions the use of such feeds is not always economically viable (A. N. N. Hristov *et al.*, 2013). It must also be considered that such feeds often have a GHG emissions heavy lifecycle (including those associated with fertiliser use, a high level of mechanisation, feed processing and transport) which must be included in any Ei calculation (Opio *et al.*, 2013). If the associated productivity improvements from the cattle systems (e.g. higher milk yields) are not sufficient they are likely to be outweighed by these lifecycle emissions and GHG emissions will be seen to increase.

Supplementing feed rations with lipid rich feeds (i.e. oils) has been seen to reduce enteric CH_4 emissions by limiting the methanogen bacteria activity in the rumen (Beauchemin *et al.*, 2008; Grainger and Beauchemin, 2011; Grainger *et al.*, 2008; Johnson and Johnson, 1995; Moate *et al.*, 2011). However, for application in developing regions several questions concerning lipid supplementation must be considered. Firstly, many query whether lipids offer an economically feasible option (Beauchemin *et al.*, 2008; A. N. N. Hristov *et al.*, 2013). Then there are both positive (Martin *et al.*, 2011) and negative (Woodward, 2006) reports as to the persistency of the mitigation effect. Potentially with most relevance to food insecure systems, the inclusion of lipids in rations has, in some studies, been demonstrated to reduce productivity alongside CH_4 emissions reductions (Jordan *et al.*, 2006a, 2006b). This includes evidence of reductions to feed intake, fibre digestibility, milk fat content and milk production (Hollmann and Beede, 2012; Hristov *et al.*, 2011, 2009, 2004; Lee *et al.*, 2011).

The inclusion of legumes (e.g. nitrogen fixing lucerne, clover, peas, beans and groundnuts) in feed rations can reduce enteric CH_4 emissions. They have a lower fibre content than most forages and a higher passage rate through the rumen

(Beauchemin *et al.*, 2008; McCaughey *et al.*, 1999). Digestibility is often greater than other tropical forages (Langyintuo *et al.*, 2003). Legumes' high content of condensed tannins can also reduce methanogen bacteria activity (Archimède *et al.*, 2011; Martin *et al.*, 2010). The increased nitrogen content of the ration can improve the value of manure for application to crops in agro-pastoral systems (Peters *et al.*, 2001; Sumberg, 2002). However, barriers to the application of legumes for developing regions have been identified, including the funds and access required for seed, and environmental restrictions to cultivation (A. N. Hristov *et al.*, 2013; Sumberg, 2002). Multipurpose leguminous grasses and trees may be more appropriate and have been successful in application worldwide (Owen *et al.*, 2012). There are also concerns that legumes fed at too greater maturity can increase CH_4 emissions (Beauchemin *et al.*, 2008; Chaves *et al.*, 2006).

Food crop straws and stovers are an important feed resource for cattle systems in the tropics, however they have insufficient nutrient contents to effectively maintain animals (Makkar, 2011). Therefore, the urea treatment of straws and stovers has commonly been suggested as an option to improve the utilisation of this resource. When straw and stover materials are treated with urea, ammonia is formed and alkaline conditions created, this compromises plant cell walls improving the digestibility and intake of the material. There is also an improvement to nitrogen content (A. N. N. Hristov *et al.*, 2013). Despite being regularly extolled as a proven technique, uptake in developing nations is generally low; often limited by poor extension efforts, inconsistent supply of straw material, and financial resource (Makkar, 2011; Owen *et al.*, 2012).

There are also measures which have been more commonly applied to commercial systems of production in developed countries. For example, ionophores (e.g. monensin), antimicrobials administered to livestock to interrupt the function of bacteria in the rumen; these reduce CH_4 emissions and improve production efficiency (A. N. N. Hristov *et al.*, 2013; McGuffey *et al.*, 2001). They have many suggested benefits such as enhanced energy metabolism, reduced risk of bloat or acidosis, improved digestibility and subsequent improvements to body condition and yield (McGuffey *et al.*, 2001). However, due to the high cost and doses required (Beauchemin *et al.*, 2008), and suggestions that improvements are not sustained long-term (Guan *et al.*, 2006), they may be limited in usefulness for developing country systems.

4.1.2. Animal health

Diseases, both infectious and parasitic, are a significant limiting factor to the productivity of SSA cattle systems (Maichomo *et al.*, 2009; Perry and Grace, 2009). Efforts to improve animal health reduce mortality and morbidity rates, increase yields and productive life spans, and reduce the need for replacement animals; subsequently system productivity is improved and Ei reduced (A. N. N. Hristov *et al.*, 2013; Perry and Sones, 2007; Shaw *et al.*, 2014). For instance diseases common in SSA, such as East Coast Fever, can be observed to increase mortality, reduce reproductive rate and limit calf growth (Gitau *et al.*, 2001; Onono *et al.*, 2013a).

Trypanosomiasis (Tryps) is a disease caused by the trypanosome parasite, transmitted by the tsetse fly vector. Due to the significant impacts of Tryps on both humans and livestock populations across SSA's tsetse belt, it has received extensive research, including that investigating the associated burdens for livestock (Hotez and Kamath, 2009; Shaw *et al.*, 2006, 2014). These include reduced animal body weights, increased mortality rates, reduced calving and milk yields and a loss of draught power provision (Shaw *et al.*, 2006). Generally symptoms and production losses are greater for introduced exotic breeds (Seck *et al.*, 2010).

Although strict health control programmes are a key feature of cattle systems in developed countries (Capper, 2011; Capper *et al.*, 2009), it has to be considered how diseases are perceived in low input systems in the developing world. Despite burdens, such as those associated with Tryps, many conditions may exist chronically in some equilibrium with the animal (Connor, 2014). In these scenarios action by livestock keepers may be constrained by perceptions, costs, and priorities (Connor, 2014; Tebug *et al.*, 2015).

4.1.3. Animal breeding

Genetic selection, or crossbreeding, has long been understood to improve the production potential of livestock, and has been a major contributor to substantial increases in cattle productivity in developed countries over the last century (Capper *et al.*, 2009). The introduction of ‘Western’ or exotic breeds (e.g. Holstein Friesian, Ayshire, Guernsey or Jersey) to developing regions, such as SSA, alongside, or crossbred, with indigenous breeds (e.g. Boran, Sahiwal or N’Dama) is fairly common (Bebe *et al.*, 2003; Devendra, 2001). Despite the successful introduction of higher productivity exotic breeds into certain scenarios (Thorpe *et al.*, 2000), genetic productivity potential is often not realised due to constraining factors. Exotic breeds require feed resources to be appropriate for their productivity potentials to be reached (Herrero *et al.*, 2009; Lukuyu *et al.*, 2012). Tropical disease burdens and a greater susceptibility to infection can also be severely limiting (Bebe *et al.*, 2003). In addition environmental conditions are more limiting for non-adapted exotic breeds. For instance, high temperatures cause heat stress; reducing both feed intake and milk yields, impairing fertility and reproduction, and limiting overall system productivity (Kadzere *et al.*, 2002; West, 2003; Wolfenson *et al.*, 2000). Regularly introduced high genetic potential animals do not reach maturity (Menjo *et al.*, 2009; Ojango and Pollott, 2002); Ei increases as inputs are wasted on animals that do not contribute to production and a greater number of animals have to be reared. Increasingly, it is recognised that the crossbreeding of exotic breeds with indigenous breeds is key to introducing a higher genetic potential for productivity, whilst still maintaining some of the resilience of indigenous breeds (Hansen, 2004; Hoffmann, 2010). Breeding for increased productivity offers an opportunity for Ei reduction, however due to the sensitivity of higher yielding breeds, crossbreeding needs to be accompanied by education and improved husbandry (van t’Hooft *et al.*, 2012).

4.1.4. Manure management

Cattle manure contains nitrogen (N), carbon (C) and water (H_2O); therefore microbial action can produce N_2O and CH_4 throughout the manure management cycle (Chadwick *et al.*, 2011). Manure collection, storage and management have significant influence on its GHG emission potential (A. N. N. Hristov *et al.*, 2013). Measures to reduce emissions can include storing manure solid to avoid anaerobic conditions favouring CH_4 emissions (A. N. N. Hristov *et al.*, 2013), or effectively roofing and flooring cattle housing to limit run-off and N losses (Rufino *et al.*, 2006).

Although manure management in SSA lacks extensive research, it is generally understood to be largely suboptimal for both productivity and emissions (Herrero *et al.*, 2013a). The effective management of manure provides opportunity to not only reduce GHG emissions, but improve the productivity of agro-pastoral systems. Reducing GHG emissions retains a greater proportion of nutrients within the manure, if used as an organic fertiliser this can then improve soil fertility (Harris, 2002; Jackson and Mtengeti, 2005; Powell, 1986; Snijders *et al.*, 2009). For extensive pastoral systems, where cattle are grazing large areas, the improvement or control of manure management is likely to be limited (Snijders *et al.*, 2009).

4.2. Barriers to mitigation measure success

The realisation of mitigation measures emissions abatement potential depends largely on the adoption of such practices by livestock keepers (Pretty, 2008; Schulte *et al.*, 2012). Barriers to adoption must be understood and solutions investigated (Gerber *et al.*, 2013b). Past attempts to introduce ‘Western’ ideas and techniques to developing nation scenarios have not always considered integration with heterogeneous systems and results are often disappointing (Oosting *et al.*, 2014; Poole *et al.*, 2013; Udo *et al.*, 2011). Potential barriers are considered from mitigation literature and summarised in Table 4.1.; Chapter three suggested that study systems are experiencing many of these barriers.

Table 4.1. Summary of potential barriers to mitigation measures in developing countries. The scale at which they are likely to act is suggested (Fa = farm level, Lo = local, Na = national).

Barriers	Fa	Lo	Na	Details
Resource competition	X	X	X	May limit the acceptability of certain measures. For example grain based animal feeds directly compete with human consumption[1].
Sociocultural role of cattle	X			The multi-functionality of cattle (e.g. status/wealth symbols, insurance, savings and dowries[2]) may restrict efforts to reduce herd sizes, using more productive animals.
Risk	X	X	X	Climate change is likely to increase risk for livestock keepers[3] and associated investment. Certain measures could be seen as an increased reliance on expensive, unreliable inputs[4] and a loss of resilience for already high risk systems.
Cost	X	X		Expensive measures are unlikely to be adopted when savings are low and credit or funding hard to access[6].
Psychology /values	X	X	X	Despite clear evidence of benefits stakeholders do not always adopt measures[7]. This may be due to culture or tradition, self-opinion or conflicts of interest[8].
Market access	X	X	X	Improved productivity, without improved infrastructure and market access, is likely to saturate local markets and limit sustainable development[5]. Conversely, infrastructure provision could introduce other stakeholders wanting a share of market profits and reducing farm gate prices[9].
Government agenda /priorities		X	X	Investment and support for agricultural development may be a low government priority. For instance countries in Africa spend an average of 4% of national budgets on agriculture, whilst those is Asia spend 8-14%[10].There can also be a divergence from formal purpose at a higher level to experience at farm level[6].
Environmental	X	X	X	Current climate currently limits application of certain measures (e.g. use of exotic cattle breeds or cultivation of improved crops).
Availability	X	X	X	Resources to apply measures may not be readily available. For example feed resources often depend on what is locally available[11].

[1]Makkar and Beever (2013); [2]Weiler *et al.* (2014) and Udo *et al.* (2016); [3]Havemann and Muccione (2011); [4]Gerber *et al.* (2013a);[5]Oosting *et al.* (2014) [6]Hounkonnou *et al.* (Hounkonnou *et al.*, 2012); [7]Moran *et al.* (2013); [8]Crane (2014, 2010); [9]Omore *et al.* (2009); [10]Fan *et al.* (2008); [11]Mekoya *et al.* (2008)

4.3. Shortlisting mitigation measures for application to study systems

Section 4.1. and 4.2. have demonstrated the variation in mitigation options that can be applied to cattle production systems, and the barriers that have potential to limit application in developing countries. Logically, options are not universally applicable to all production systems, therefore system level evaluation and shortlisting of measures based on rational criteria is required. Mitigation measures, from the categories summarised in section 4.1., were shortlisted in varying ways. For all categories of mitigation measures there is a potential bias in the literature towards measures that are more amenable to quantitative analysis.

4.3.1. Animal health mitigation measure options

The diseases that reduce cattle productivity in Senegal are likely to be highly varied (D'Alessandro *et al.*, 2015; Tebug *et al.*, 2015). To remain within the scope of this project, three priority health challenges were identified. This was done through:

a) reviewing the livestock keepers' answers to SDG project survey questions concerning major cattle health problems; and
b) interviews and FGDs with experts and livestock keepers during fieldwork in Senegal (Chapter three).

The three major health constraints to cattle production were defined as:

Foot and Mouth Disease

Foot and Mouth Disease (FMD) is a highly contagious virus, with symptoms including fever, vesicular eruptions on the feet and mouth, and associated reductions to animal productivity. FMD is rare in developed countries, where responses to infection include quarantine and slaughter measures (Blowey and Weaver, 2003). However, vaccination is possible and may be more suitable for SSA where FMD is often endemic (Barasa *et al.*, 2008; Jemberu *et al.*, 2014).

Lumpy Skin Disease

Lumpy Skin Disease (LSD) is a *Capripoxvirus*, with symptoms including skin nodules all over the body, fever and associated reductions to animal productivity (Blowey and Weaver, 2003). Vaccination for LSD is available (Al-Salihi, 2014; Ayelet *et al.*, 2013; Hunter and Wallace, 2001).

Trypanosomiasis

Trypanosomiasis (Tryps) is caused by the trypanosome parasite infection and is spread by the tsetse fly vector (Blowey and Weaver, 2003). Symptoms include reductions in fertility, growth rates, milk yields and animal strength or stamina (Connor, 2014). Development of vaccines to prevent Tryps has been limited in success (Black and Mansfield, 2016; Magez *et al.*, 2010), whilst drugs (trypanocides) for treatment are available, but often misused (Black and Mansfield, 2016; Connor, 2014). Currently, control or eradication of the tsetse fly vector appears the best option for reducing the productivity burdens associated with Tryps (Bouyer *et al.*, 2014; Shaw *et al.*, 2006, 2013; Vreysen *et al.*, 2013). Measures include insecticide sprays, traps, live bait (e.g. pour-on insecticide for livestock), and the release of sterile male tsetse (Vreysen *et al.*, 2013).

4.3.2. Animal breeding as a mitigation measure option

As discussed in Section 4.1.3. breeding for increased productivity can be used as a mitigation measure. Seven production systems were identified within the SDG project sample (based on herd management and the dominant cattle breed, see Section 2.2.). These systems have varying levels of introduction of higher yielding breeds; therefore, a comparison between the Ei of these different systems will be used to assess the potential to use animal breeding as a mitigation measure.

4.3.3. Manure management mitigation measure options

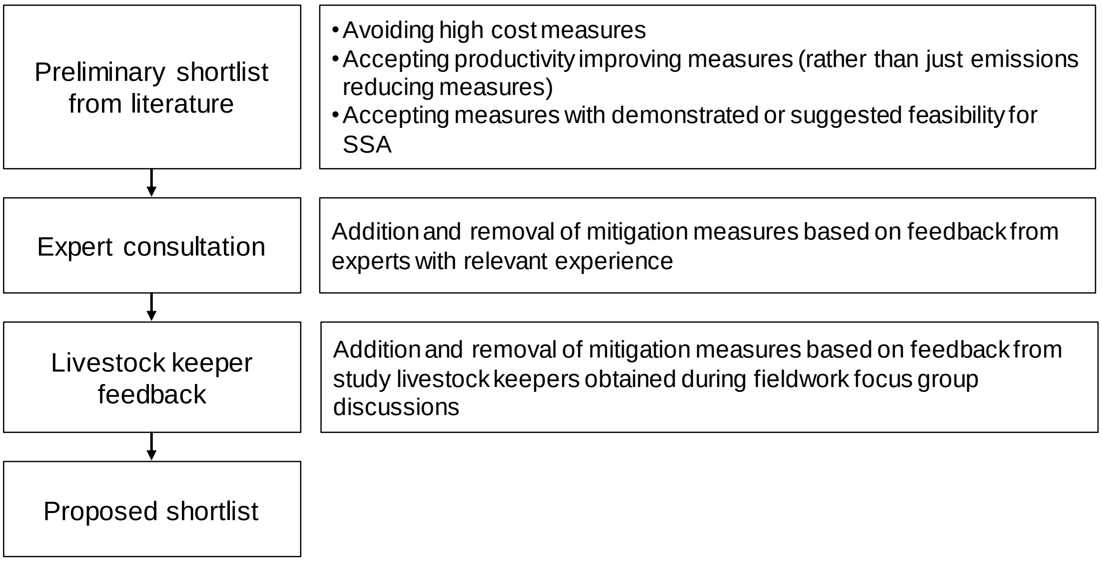
Improving manure management is not considered further in this project as a mitigation measure option for two reasons (information was derived from the SDG survey results):

a) The cattle in many of the study systems spend a large proportion of time grazing extensive pasture where manure collection is not practical; and

b) any manure collected during the night tethering of cattle or stall feeding is largely stored staked, solid and dry, and is a relatively minor source of GHG emissions.

4.3.4. Animal nutrition and feed mitigation measure options

There is a broad range of feed related mitigation options, therefore a process of shortlisting was carried out to determine measures appropriate for the study systems, this is summarised in Figure 4.1. and discussed in greater detail in the following section.



- Avoiding high cost measures
- Accepting productivity improving measures (rather than just emissions reducing measures)
- Accepting measures with demonstrated or suggested feasibility for SSA

Addition and removal of mitigation measures based on feedback from experts with relevant experience

Addition and removal of mitigation measures based on feedback from study livestock keepers obtained during fieldwork focus group discussions

Figure 4.1. Summarised shortlisting process used to derive a list of feed related mitigation measures relevant to the study systems.

4.4. Shortlisting feed related mitigation measures

4.4.1. Preliminary shortlisting

The first stage of shortlisting was to review available literature concerning feed options that exist for cattle systems to mitigate GHG emissions (see Section 4.1.1). In the first instance broad mitigation measure themes that would likely be applicable to the study systems were shortlisted; these included diet supplements, feed choice (selection of different ingredients in a ration) and feed management (management of specific feed materials). Where possible and relevant specific measures were named (Table 4.2.). As shown in Figure 4.1., during this preliminary stage of shortlisting, measures were avoided if they had high financial cost, did not improve productivity (i.e. benefit food security), or had no evidence of feasibility for application in SSA production systems. Table 4.2. summarises this step of shortlisting.

Table 4.2. Preliminary shortlisting of feed related mitigation measures for modelling of application to the study production systems

Theme	Specific example	Description	Financial cost (High/Medium/ Low)[a]	Evidence of sustained productivity improvement	SSA Feasibility	Primary shortlist inclusion
Diet supplement	Ionophores	See Section 4.1.1	High[1]	Mixed[2,3,4]	Unlikely[1,5]	No
	Electron acceptors	Alternative electron acceptor (e.g. nitrate) suggested as highly effective in CH$_4$ reductions[3,6]	High[1]	No[3]	Unlikely[3]	No
	Plant compounds (e.g. tannins)	Reduce CH$_4$ production through direct toxic effect on methanogens in the rumen[7,8]	High[1]	No[3,7,9]	Unlikely[1]	No
	Dietary lipids	See Section 4.1.1	High[1,10]	Mixed[3,9]	Unlikely[1,11]	No
Feed choice	Concentrate feeds	See Section 4.1.1	Medium[3]	Yes[3]	Situation specific[9,12,13,14]	Yes
	Legume forages[b]	See Section 4.1.1	Medium[15]	Yes[3]	Situation specific[10,14,15,16]	Yes
	Cereal silages[b]	CH$_4$ reduced through increased starch, intake and passage rate. Increase in energetically efficient post-ruminal digestion of feed[9] (Box 4.1.)	Medium	Yes[17]	Situation specific[14,18,19,20]	Yes
Feed management	Pasture forage management[c]	Excessive maturity increases cell wall lignin (fibre) and reduces digestibility and intake[9,10,21] (Box 4.1.)	Low	Yes[21]	Situation specific[14,20]	Yes
	Alkaline (urea) treat crop stover	See Section 4.1.1	Medium	Yes[22,23]	Indicated[14], but low use[22,24]	Yes

[a] An assumption made based on literature review; [b] In place of poor quality forages; [c] In particular grazing when pasture plants are at optimal maturity for nutritional value

[1] Dickhöfer *et al.* (2014); [2] Callaway *et al.* (2003); [3] Gerber *et al.* (2013a); [4] Guan *et al.* (2006); [5] Grainger *et al.* (2010); [6] Beauchemin and McGinn (2006); [7] Grainger *et al.* (2009); [8] Carulla *et al.* (2005); [9] Beauchemin *et al.* (2008); [10] Hristov *et al.* (2013); [11] Knapp *et al.* (2014); [12] Makkar and Beever (2013); [13] Lovett *et al.* (2006); [14] Lukuyu *et al.* (2012); [15] Sumberg (2002); [16] Herrero *et al.* (2013b); [17] O'Mara *et al.* (1998); [18] Otieno *et al.* (1991); [19] Ogle (1990); [20] Goopy and Gakige (2016); [21] Randby *et al.* (2012); [22] Makkar (2011); [23] Chenost and Kayouli (1997); [24] Owen *et al.* (2012).

4.4.2. Expert consultation

Following the shortlisting of feed related mitigation measures in Section 4.4.1., experts with experience working with livestock in SSA were consulted (expert details and relevant experience are summarised in Table 4.3.). This method has been employed in previous studies (Gerber *et al.*, 2013a; Macleod *et al.*, 2010). Measures were discussed and suggestions made, some measures were removed and some additional measures or details suggested (Table 4.4. summarises this process).

Table 4.3. Details of consulted experts (consultation method detailed). Experience is included to demonstrate qualification to assist in secondary shortlisting.

Consulted individual	Evidence of relevant experience
Augustine Ayantunde *ILRI regional representative, West Africa* (email communication)	• Senior ILRI livestock scientist • 20 years of experience in ruminant nutrition and feed resource evaluation in the West African Sahel
Ben Lukuyu *ILRI country representative, Uganda* (email communication)	• Specialist for East Africa Dairy Development (ILRI) • Expertise in animal nutrition and sustainable productivity
Alan Duncan *ILRI Principal Livestock Scientist* (face-to-face meeting)	• Technical background in livestock nutrition • Interest in institutional barriers to livestock feed development • Responsible for the development/application of ILRI's FEAST[a] to support feed development strategies for smallholders
Timothy Robinson *FAO-AGAL* *(Previously ILRI Principle Scientist)* (email communication)	• Livestock specialist, experience in both Africa and Asia • Expertise in: livestock distribution and abundance, production systems, supply and use of animal-source foods, livestock disease, risk and poverty
Karen Marshall *ILRI Scientist, Animal breeding and genetics* (email communication)	• Research scientist at ILRI • Specialist in increasing livestock productivity in developing countries • Experience working on a range of production systems/species in Africa and Asia
Guillaume Duteurtre *CIRAD agricultural economist* (email communication)	• Agricultural economist and agronomist with experience in developing regions • Based in Dakar, Senegal, 2003 to 2009

[a] 'The Feed Assessment Tool (FEAST) is a systematic method to assess local feed resources availability and use' (Duncan, 2014).

Table 4.4. Summary of expert consultation; the second stage of shortlisting feed related mitigation measures for application to study systems

Mitigation measure[a]	**Specific measures identified**[b]	**Notes from consultation**	**Shortlisting outcome**
Inclusion of concentrate feeds	a) Groundnut cake b) Purchased concentrate (compound) feed	Universally accepted, although highly dependent on availability to livestock keepers. Importance of quality of concentrate feed. Importance of strategic supplementation to improve use of roughages.	Improve baseline rations with: a) Groundnut cake b) Purchased compound feeds
Legume forages replace poor forages	Cowpea forage	Useful to improve the utilisation of poorer quality roughages, improve digestibility of the ration and promote feed intake. Likely that legume material will come from residues of legume food crops, so availability dependent.	Replace poor forages with cowpea hay/forage
Maize or cereal silages replace poor forages	Maize or cereal silages replace poor forages	Mixed response, environmental and plant conditions do not promote silage making. Storage of silage is also a challenge.	Removed
Pasture forage management	a) Graze pasture at appropriate maturity b) Create fodder banks	Universally accepted. Suggestion that hay is harvested at appropriate plant maturity for nutritional value, in addition to grazing and fodder banks. Challenge of communal land restricts motivation for individuals to improve pasture management.	a) Graze pasture at appropriate maturity b) Maintain fodder banks c) Harvest pasture (hay) when at appropriate maturity
Alkaline (urea) treatment of crop stovers	Urea treatment	Accepted, but warn that not widely adopted in SSA, and access to urea, cost and labour could be prohibitive. Requires extension and education to ensure appropriate application.	Urea treat crop stovers in the diets

[a] Preliminary shortlist following literature review

[b] Specific measures identified (where applicable) through the assumption that appearance in current rations shows evidence of access to a resource

4.4.3. Study livestock keepers’ feedback

The focus group discussions (FGDs) with study livestock keepers conducted during fieldwork (Chapter three) provided a final stage of shortlisting for feed related mitigation measures. Livestock keepers were asked to discuss both broad ideas for mitigation measures; then more specific measures were examined to understand the likelihood of uptake. Challenges to uptake were considered for the mitigation measure shortlist (Table 4.4.). The FGDs demonstrated communal land to be a key challenge to grazing management and maintenance of fodder banks (Section 3.3.4.5.). Therefore, these two mitigation measures were removed. Improvements to hay making, through harvesting at optimum maturity, was maintained as a mitigation measure as it was assumed that the challenge of communal land is reduced as the resource is removed and stored at the households. Despite FGDs suggesting that there are barriers to the uptake of all mitigation measures (e.g. finance), all other measures were maintained as they were after the expert consultation stage (Table 4.4.). The barriers will need to be considered in consideration of results and conclusions.

4.4.4. Mitigation measure shortlist

Table 4.5. presents the final list of mitigation measures, following the three stages of shortlisting, which were selected as appropriate to have their application to study systems modelled. The method for this modelling and results will be discussed in Chapter five.

Table 4.5. The final list of mitigation measures, suggested as appropriate for application to the study systems following the three stages of shortlisting.

Category	Mitigation measure	Description
Feed/nutrition	Improved ration using groundnut cake	High protein feed, locally available as an agro-industrial by-product and present in 'baseline' rations at varying levels (high digestibility).
	Improved ration using purchased (compound) concentrate feed	Locally available high energy feed, present in 'baseline' rations at varying levels (high digestibility).
	Improved timing of hay harvesting	Hay provides a feed resource for times of shortage. Effective timing of haymaking can maximise protein content and digestibility.
	Urea treat crop stovers in the ration	Treating stovers with urea improves digestibility and protein content.
	Replace poorer forages with cowpea hay	A legume crop, cowpea provides a high quality protein source and a greater level of digestibility compared to other conserved forages in these systems.
Health	Remove LSD burden	Effective vaccination of herds
	Remove FMD disease burden	Effective vaccination of herds
	Remove Tryps burden	Remove tsetse fly vector
Breeding	Promote use of improved breeds (higher productivity)	Improve productivity of herds

LSD = Lumpy Skin Disease; FMD = Foot and Mouth Disease; Tryps = Trypanosomiasis

CHAPTER FIVE

MODELLING THE APPLICATION OF MITIGATION MEASURES

5.1. The Global Livestock Environmental Assessment Model

The Global Livestock Environmental Assessment Model (GLEAM) was developed by the Food and Agriculture Organization of the United Nations (FAO) 'to help improve the understanding of livestock GHG emissions along supply chains, and to identify and prioritize areas of intervention to lower sector emissions'[6] (Gerber *et al.*, 2013b; MacLeod *et al.*, 2017); for instance the model was used for the FAO reports 'Greenhouse gas emissions from pork and chicken supply chains, a global life cycle assessment' and 'Greenhouse gas emissions from ruminant supply chains, a global life cycle assessment' (MacLeod *et al.*, 2013; Opio *et al.*, 2013).

The current version of GLEAM (V2.0) is a static model, using a lifecycle assessment (LCA) approach (defined in ISO standards 14040 and 14044 (ISO, 2006a, 2006b)) to simulate livestock production systems and enable a holistic assessment of environmental performance; specifically GHG emissions (CH_4, N_2O and CO_2) (FAO, 2017). GLEAM, as used by the FAO, runs in a Geographic Information System environment, enabling global scale assessments. However, for the purpose of this study an Excel version of GLEAM was used; this works at an individual herd level allowing quicker analysis of processes and mitigation measures for specific herd scenarios of cattle production. The system boundary for this assessment includes cradle to farm-gate (emissions categories included are summarised in Table 5.1.). Cattle in the study systems are reared for both milk and meat (Section 2.5.1.); therefore, reporting of Ei of production uses kg CO_2 equivalent (Section 1.2.) per kg of protein (kg CO_2eq/ kg of protein) as a functional unit (Figure 5.1. demonstrates how this unit is calculated in GLEAM). This allocation of emissions to edible outputs only can be misleading for systems in developing countries (Udo *et al.*, 2016; Weiler *et al.*, 2014) (section 1.3.). However, with suggestion that for a large proportion of study households cattle are reared for protein (Section 2.5.1.), and difficulty in accurately quantifying other values of cattle; only protein output is considered in the analysis.

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[6] http://www.fao.org/gleam/en/

Table 5.1. Greenhouse gas emissions categories included in the calculation of emissions intensity for protein production.

Emissions category	Emissions sources	On farm	Off farm
Enteric CH_4	Enteric fermentation by cattle on the farm	✓	
Manure CH_4	Manure stored on the farm prior to application to land	✓	
Manure N_2O	Manure stored on the farm prior to application to land	✓	
Feed N_2O	N applied to land, including fertilisers (inorganic and organic) and manure from grazing animals	✓	✓
Feed CO_2 (energy use)	Manufacture of fertilisers Production, processing and transportation of feeds Mechanised field operations		✓

N = Nitrogen

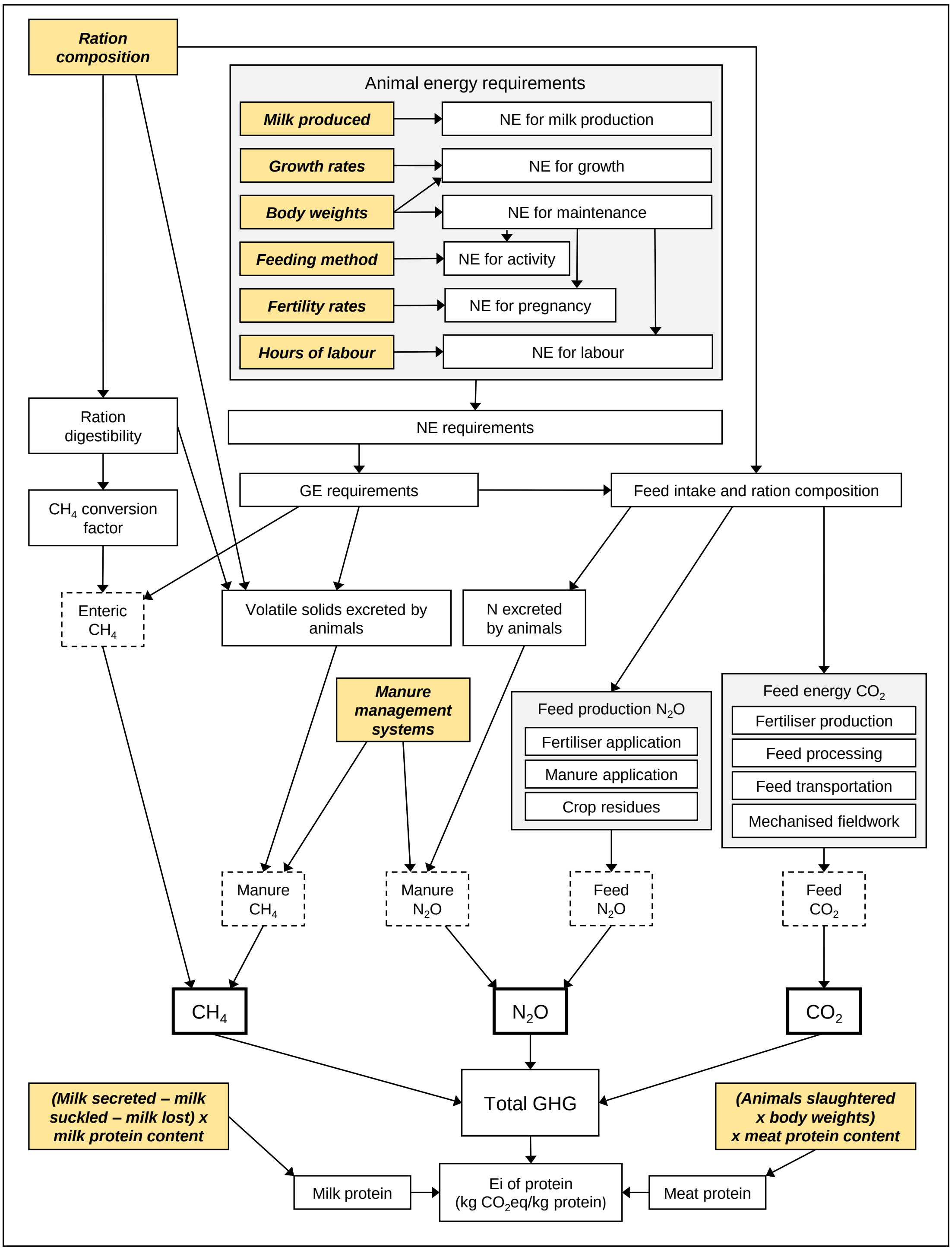

Figure 5.1. Summary of the calculation of emissions intensity (Ei) for protein production (kgCO_2eq/kg protein) within the version of GLEAM used in this study. Highlighted boxes with bold italicised text indicate model user inputs. Dashed boxes indicate the emission categories included in the assessment. NE = Net energy, GE = Gross energy, CH_4 = Methane, N_2O = Nitrous oxide, CO_2 = Carbon dioxide, N = Nitrogen.

5.2. Baseline system emissions intensities

Baseline production systems were modelled using GLEAM for typical herds, with eight adult cows (GLEAM also calculates and includes the total herd structure, including young stock and bulls), for each of the seven defined herd types (Table 2.2.); discerning the current Ei of protein production. Input data to model these defined herds is shown in full with source information in Appendix B. To allow visualisation alongside the results, Table 5.2. summarises key input data.

Table 5.2. Summary of input data for the calculation of emissions intensity for baseline production systems ('+' indicates comparable levels of management (Section 2.2.2)).

Model parameter	**Unit**	**IZ**[a]		**IZ x GZ**[a]		**IZ x BT**[a]		**BT**[a]
		+	**++**	**+**	**++**	**++**	**+++**	**++++**
AF body weight	kg	294	317	302	309	333	414	433
Milk offtake	kg/year/lactating cow	323	877	411	989	937	2032	2197
Age at first calving	years	4.3	3.8	3.7	3.7	3.5	3.5	3.3
AF fertility rate	proportion calving/year	0.57	0.63	0.55	0.71	0.55	0.71	0.63
AF replacement rate	proportion replaced/year	0.21	0.19	0.19	0.19	0.18	0.18	0.18
AF death rate	proportion dying/year	0.02	0.02	0.02	0.02	0.03	0.03	0.07
Ration digestibility	% of gross energy	55.1	56.8	55.5	55.5	57.6	59.4	63.0
Ration N content	g/kg	17.6	19.2	17.9	18.3	21.4	23.4	25.8

[a] For details of breed types see Section 2.2.1.
AF = Adult female

The Ei for protein production (kg CO_2eq/ kg of protein), and the related efficiency of protein production (defined as kg of protein annually produced per kg of herd animal biomass) for the baseline study systems (systems of production as they currently exist) are shown in Figure 5.2.. Key emissions categories include enteric CH_4, feed related N_2O (largely from organic N in urine and manure both deposited directly by animals whilst grazing and collected then spread), and CO_2 from energy use in the production of groundnut meal and purchased concentrate (compound) feed. Figure 5.2. shows a defined variation in Ei between baseline systems of production and suggests the expected negative relationship with system productivity (protein yield efficiency).

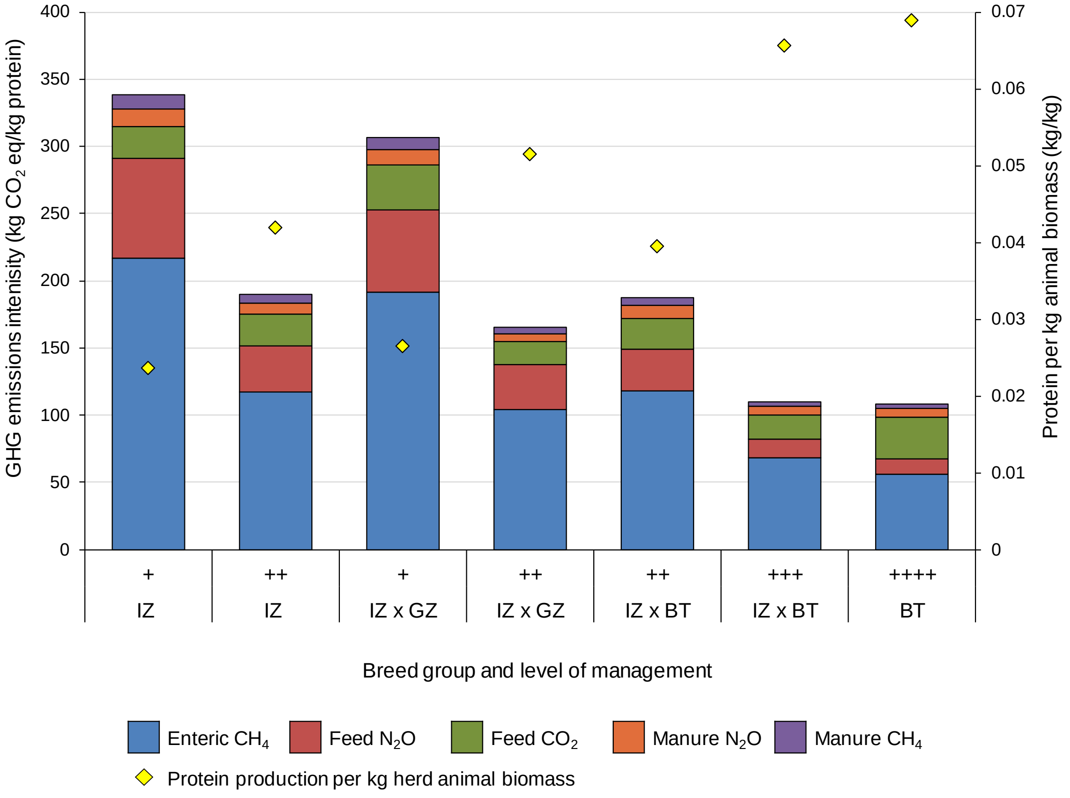

Figure 5.2. Emissions intensity (kgCO_2eq/ kg protein) (bars, left y-axis) and annual protein production per kg of animal biomass (kg/kg) (diamonds, right y-axis) by breed type and management level (indicated by '+') (Section 2.2.), based on calculations for typical herds with eight adult cows.

5.2.1. Emissions intensity sensitivity analysis

Although the input data used to model the production systems are largely based on primary data gathered through the SDG project, there are still uncertainties (through both the use of averages and assumptions to represent systems of production, Appendix B gives further details) that may affect results. Therefore, a sensitivity analysis was conducted to discern input parameters to which the Ei was most sensitive. Herd level input parameters (that may be changed when baseline systems are altered to demonstrate the application of mitigation measures) were in turn altered by +10% and -10% (i.e. multiplied by 1.1 and 0.9, respectively). Table 5.3. summarises the influence of these alterations to individual input parameters on the Ei result. Ration digestibility is most influential on Ei, with an increase in digestibility causing a decrease in Ei. Figure 5.1. demonstrates that ration digestibility effects enteric CH_4 (understood to be the most significant source of GHGs from cattle systems (Opio *et al.*, 2013)) and determines animal feed intake requirements, thus influencing the magnitude of all GHGs associated with feed material lifecycles.

Table 5.3. Sensitivity analysis results, showing the percentage change in emissions intensity (kg CO_2eq/ kg protein) when individual input parameters are altered by -10% and +10%. Values shown are averages for results for all seven defined herd types.

Input parameter	-10%	+10%
Ration digestible energy	25.07	-16.95
Milk yield	6.02	-5.28
Adult female fertility rate	6.02	-4.78
Adult female body weight	-2.99	2.80
Age at first calving	-2.97	3.40
Bull:cow ratio	-1.40	1.42
Ration nitrogen content	-0.58	0.58
Calf birth weight	0.11	0.09
Adult female replacement rate	-0.08	0.08
Death rate (averaged across cohorts)	-0.01	0.01

5.2.2. Variation in baseline system emissions intensities

Modelling of the baseline production systems for the defined herd types demonstrates variation in the GHG Ei (kg CO_2eq/ kg protein) (Figure 5.2.). As well as the key role played by ration digestibility, this variation can be linked to the efficiency of protein production, as is evident in Figure 5.2. (kg of protein production per kg of animal biomass). The sensitivity analysis (Table 5.3.) demonstrates milk yields and fertility rate are likely to have the greatest effect on both protein production efficiency and Ei.

The relationship between Ei and productivity is well recognised in the literature (Capper, 2011; Capper *et al.*, 2011, 2009; Gerber *et al.*, 2011). Increased productivity results in a greater proportion of energy being distributed to protein production, and less to animal biomass maintenance. This increases the protein produced per kg of GHG emitted, and subsequently reduces the Ei.

Herd structure

The structure of herds is commonly recognised as a key determinant of Ei for different systems of production (Opio *et al.*, 2013). To maintain productive herds some proportion of non-productive animals are required (i.e. animals not directly yielding human edible protein, including dry cows, mature bulls, and some proportion of young stock). If reproductive performance is low or mortality rates high, a greater proportion of non-productive animals will be required. This reduces herd level feed use efficiency; Ei increases as there is a greater demand on feed energy to maintain animals, instead of to produce protein. The herd structures for the Senegal study systems can be seen in Figure 5.3.; these are calculated by GLEAM based on age at first calving or maturity, replacement and offtake rates, bull to cow ration, and mortality rates. There is some difference in the proportions of 'productive' and 'non-productive' biomass in the defined herd types; this will play a role in the baseline Ei variation (Figure 5.2.). For instance, herd types IZ x GZ ++ and IZ X BT +++ have the greatest proportion of productive animals, and have low Ei compared to the majority of other herd types (excluding BT ++++, which has a high ration digestibility and milk yields strongly influencing the Ei).

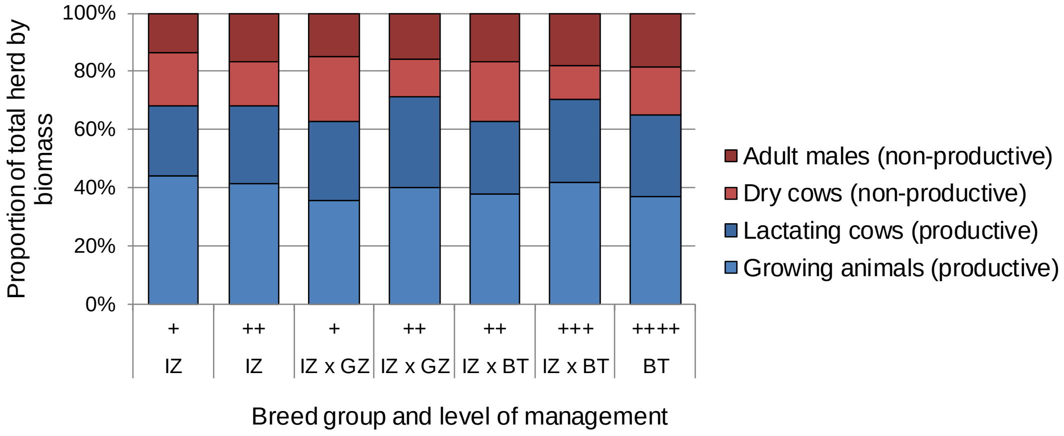

Figure 5.3. Herd structure, presented as the proportion of total herd biomass 'productive' or 'non-productive' in relation to human edible protein, for each of the defined herd types (Section 2.2.)

Allocation of emissions

As previously mentioned, the allocation of GHG emissions is to protein output only. GLEAM does have the functionality to consider draught power provided by cattle; allocating emissions proportionally based on how much energy is used to provide the draught power. However, for the Senegal study systems draught power provided by cattle is negligible as the use of horses is more common. Despite recognition of the potential value of draught power no emissions are allocated to such a function.

Effective management and resilience

Figure 5.2. shows that both 'better' managed indigenous Zebu (IZ++) and 'better' managed indigenous Zebu by Guzerat Zebu cross (IZ x GZ++) herds have lower Ei than 'poorer' managed herds of breed types with likely higher genetic productivity potential (IZ x GZ+ and IZ x BT++, respectively) (see Section 2.2.1.). This demonstrates the importance of suitable management for animals to reach full production potential, and that consequently breeds of high genetic potential are not always optimal under challenging conditions with limited inputs. Crossbred animals that introduce some productivity potential but retain some of the resilience of indigenous breeds are often more appropriate (Marshall *et al.*, 2016b), and in this instance demonstrate lower Ei than systems which may have greater genetic potential. In addition, there is very little difference in the Ei of indigenous Zebu by Taurine cross herds (IZ x BT +++; 110 kg CO_2eq/ kg of protein) compared to Taurine herds (BT ++++; 108 kg CO_2eq/ kg of protein). Consequently, interventions to improve productivity must be designed as packages to be successful (e.g. improved breeds, with well managed health and adequate feed).

5.2.3. Comparison of emissions intensities to other studies

Table 5.4. shows weighted averages for the Ei of milk and meat from the Senegal study baseline systems; alongside are the results of other studies considering cattle production globally and within SSA. These studies are comparable to the results from the Senegal study; the FAO study uses GLEAM (Opio *et al.*, 2013), whilst Weiler *et al.* (2014) and Udo *et al.* (2016) use IPCC (2006) guidelines, on which GLEAM is largely based.

The FAO suggest that the global average and arid SSA Ei for cattle milk production (100% sourced from dairy herds) to be 2.8 kgCO$_2$eq/ kg milk and 10.0 kgCO$_2$eq/ kg milk, respectively (Opio *et al.*, 2013). The average Ei for milk production in the Senegal study (8.4 kgCO$_2$eq/ kg milk) is lower than that suggested for arid SSA, but greater than the global scale. The Senegal study Ei is also greater than that for the studies of Kenyan cattle systems by Weiler *et al*. (2014) and Udo *et al*. (2016). Table 5.4. demonstrates how differences in feed ration digestibility and milk yields are likely contributors to this Ei variation.

However, the differences in Ei for meat production cannot be so easily explained by the same model parameters, or by fertility rates or body weights. The Senegal sample Ei (30.6 kgCO$_2$eq/ kg meat) is likely to be less than both the Ei for arid SSA (75.0 kgCO$_2$eq/ kg meat) and globally (46.2 kgCO$_2$eq/ kg meat) due to the difference in sources (dairy herds or beef herds) of cattle meat, and the Ei of production from those sources. Generally beef herds produce meat with higher Ei than meat sourced from dairy herds; on a global scale Ei are 67.8 and 18.4 kgCO$_2$eq/ kg meat, respectively (Opio *et al.*, 2013). Dairy herds have a large proportion of total protein produced coming from milk, so a greater proportion of emissions are allocated to the milk proportion of total protein, and less allocated to any meat protein. Whereas for beef herds meat production is the only source of protein, so bears the full emissions burden (Opio *et al.*, 2013). On the global scale around 44% of cattle meat is sourced from dairy, with 56% coming from beef herds. For SSA 59% of cattle meat is sourced from dairy herds (with Ei 30-40 kgCO$_2$eq/ kg meat) and 41% comes from beef herds (with Ei 110-120 kgCO_2eq/ kg meat) (Opio *et al.*, 2013). In comparison the meat in the Senegal study systems all comes from herds producing both milk and meat (with, on average 59% of protein from milk and 41% from meat), therefore total emissions are allocated accordingly to milk and meat, reducing the meat Ei.

Table 5.4. The variation in the emissions intensity (Ei) of produce from the Senegal study, alongside Ei presented by other studies considering global and SSA cattle production.

Source	Ei	Ei unit (kg CO_2eq per)	DE%[A]	Milk yield[B]	Fertility[C]	Body weight[D]
Senegal study	8.4*	kg milk	56.8*	905*	61*	328*
FAO Global[1]	2.8	kg milk	*65.5*	*3370*	*79*	*470*
FAO SSA Arid[1]	10.0	kg milk	*57.3*	300	72	*303*
Weiler *et al.* Kenya[2]	2.0	kg milk	-	1456	-	-
Udo *et al.* Kenya[3]	1.8†	kg milk	-	1649	-	-
Senegal study	30.6*	kg meat	56.8*	-	61*	328*
FAO Global[1]	46.2	kg meat	*64.7*	-	*81*	*470*
FAO SSA Arid[1]	75.0	kg meat	*57.3*	-	*67*	*303*

[1] Opio *et al.* (2013);
[2] Weiler *et al.* (2014);
[3] Udo *et al.* (2016);
[A] DE%: Ration digestibility, digestible energy as a percentage of gross energy;
[B] Milk yield: kg/cow/year
[C] Cow fertility rate (%)
[D] Cow body weight (kg)
*An overall Senegal study average weighted by the number of households of each defined herd type;
†Udo *et al.* (2016) allocate emissions to functions of cattle beyond protein production;
Numbers in *italics* are calculated based on data available in the relevant sources.

The range of Ei demonstrated within the Senegal study (Figure 5.2.), and amongst other studies of SSA cattle systems, emphasises that production systems must have their heterogeneity sufficiently recognised and deserve specific analysis, if accurate suggestion of their climate change impact is to be made. Additionally, suggestions of abatement potential through the application of mitigation measures must be considered from an accurate baseline.

5.2.4. Specific emissions categories for baseline systems

Enteric methane

Globally enteric CH_4 is the main source of GHG emissions from cattle systems; it is particularly prevalent in the total emissions from systems in developing regions where feed rations are generally of a low quality (Opio *et al.*, 2013). This is also evident in the baseline systems from the Senegal study, with enteric CH_4 contributing to between 52% and 64% of total emissions (Table 5.5.). The ranging prevalence of enteric CH_4 between herd types is driven directly by the varying digestibility of the feed rations in each system (Table 5.2.). The herd type with the lowest feed ration digestibility (IZ +, 55.1%) has the highest percentage of emissions from enteric CH_4 (64%), whilst the herd type with the highest feed ration digestibility (BT ++++, 63%) has the lowest percentage of emissions from enteric CH_4 (52%). When considering reducing Ei of production through improving productivity, it is important to consider that if animal performance is improved (for instance by improving feed rations digestibility) they will require a greater feed intake to fulfil the increased energy requirements of increased production. This is likely to increase total enteric CH_4 emissions per animal. Reduction in Ei therefore relies on protein production increasing by a greater proportion then enteric CH_4 emissions.

As enteric CH_4 is a key component of total emissions from cattle systems, the calculation to determine respective emissions is influential in the total GHG emissions and Ei results. GLEAM uses IPCC (2006) Tier 2[7] methodology to calculate enteric CH_4 emissions based on the energy requirements of cattle (Figure 5.1.). Past studies have cited a lack of accurate data concerning animal populations as introducing significant uncertainty to the enteric CH_4 calculation (Opio *et al.*, 2013).

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[7] IPCC Tiered approach to the reporting of GHG emissions (IPCC, 2006)
Tier 1: the simplest approach relying on default emission factors
Tier 2: more complex approach requiring country-specific data
Tier 3: additional complexities designed to address national circumstances, with inclusion of models considering system details (e.g. seasonal/temporal variation and mitigation strategies). Requires high-resolution data.

Through access to extensive data from the SDG project, the feed ration information and animal production parameters used here can be considered more realistic than many past studies, particularly in developing regions. This gives increased confidence in the calculation and comparison of enteric CH_4 emissions from the different herd systems observed in the Senegal study.

However, despite the detailed information from the SDG information, it is important to discuss the uncertainty with regards to the methodology for estimating enteric methane emissions. The IPCC Tier 2 methodology calculates the proportion of GE intake by the animal that will be lost as CH_4 during enteric fermentation, using a fixed CH_4 conversion factor for dairy cattle (IPCC *et al.*, 2006). The FAO required GLEAM to 'better reflect the wide-ranging diet quality and feeding characteristics globally', therefore the conversion factor was calculated based on the digestibility of feed rations (conversion factor = 9.75 – 0.05 x DE%) (Opio *et al.*, 2013). Despite this being a valid attempt to link the quality of feed rations to the magnitude of enteric methane emissions it introduces uncertainty to the overall emissions intensity calculation. Empirical approaches are attempting to reduce this uncertainty by improving our understanding of enteric methane conversion factors for specific production systems (Cambra-López *et al.*, 2008; Jaurena *et al.*, 2015; Kaewpila and Sommart, 2016).

Table 5.5. Division of total GHG emissions intensity for protein production (kgCO_2eq/kg protein), for each breed type and management level (Section 2.2.)

GHG emission category	IZ +	IZ ++	IZ x GZ +	IZ x GZ ++	IZ x BT ++	IZ x BT +++	BT ++++
Enteric CH_4	64%	62%	62%	63%	63%	62%	52%
Feed N_2O	22%	18%	20%	20%	16%	13%	11%
Feed CO_2	7%	13%	11%	10%	12%	16%	28%
Manure N_2O	4%	4%	4%	4%	5%	6%	6%
Manure CH_4	3%	3%	3%	3%	3%	3%	3%

Feed production related emissions

Emissions from feed production represent from 28% (IZ x BT ++) to 39% (BT ++++) of total herd emissions and include both N_2O and CO_2 (Table 5.5.). These emissions are associated with the production processes for feed; including any fertilisers or manure deposited on croplands or pastures, mechanisation, feed processing, and feed transportation. The magnitude of these emissions categories are related to the volume of feed required to produce units of protein, which is dependent on herd feed conversion efficiency. For instance if animals take longer to reach maturity and become productive, at any one time there will be more non-productive animals being maintained for a given quantity of protein produced by the herd. As the Senegal study systems produce both milk and meat, they will have higher feed conversion efficiencies than if they were to only produce one product. This greater volume of protein produced reduces the impact of any non-productive animals required.

Feed nitrous oxide

GLEAM considers N_2O emissions from any applied N fertiliser, manure deposited on pastures whilst animals graze, manure actively applied to land, and crop residues left in fields. The use of fertiliser and active application of manure to land is minimal for the Senegal study systems, it is limited to imported crops (e.g. maize from Brazil) and a portion of local food crops from which by-products are used (e.g. groundnuts and millet). The predominant source of feed N_2O from the Senegal study systems is manure deposited on pasture (on the study farms) whilst the animals are grazing. Those systems which spend less time grazing and more time housed (IZ x BT and BT) have a lower proportion of total emissions from feed N_2O. As discussed by Opio *et al.* (2013) the Tier 1 methodology used by GLEAM for calculating N_2O emissions only considers fertiliser and manure application, ignoring other potentially important factors, such as climate, soil types and tillage practices. This limited methodology and uncertainty to the accuracy of N application information restricts the accuracy of the N_2O quantification. However, any error is likely to be consistent across the Senegal study systems and comparisons between them can be made with confidence.

Feed carbon dioxide

GLEAM considers CO_2 emissions relating to any feed production process, this includes energy use for fertiliser production, feed processing and transport, and mechanised fieldwork. Therefore, feed related CO_2 emissions contribute a noticeably greater proportion in the total emissions from those systems which use a greater proportion of feed resources which have processing lifecycles (IZ x GZ +++ and BT ++++); these include purchased concentrate (compound) feed and groundnut cake.

Manure related emissions

Emissions from manure represent between 7% and 9% of total herd emissions and include both CH_4 and N_2O (Table 5.5.). Emissions from manure depend on storage techniques, climate, and manure composition (determined by feed composition). Manure stored in a liquid state (e.g. lagoons) creates anaerobic conditions facilitating methanogens and increasing CH_4 emissions. Emissions are further increased as higher temperatures increase methanogen activity (Chadwick *et al.*, 2011; Opio *et al.*, 2013). However, within the Senegal study systems if manure is collected and stored or left on pasture, it is dry, favouring the direct emission of N_2O. N_2O emissions also depend on the N excreted by animals (Chadwick *et al.*, 2011; Opio *et al.*, 2013). Across the Senegal study systems the proportion of N fed to animals and retained is fairly constant (between 30 and 40%). Instead it is the cattle in the systems which receive the greatest quantity of N in their feed rations (Table 5.2.), with greatest N surpluses, that have a greater proportion of manure N_2O emissions (IZ x GZ and BT).

Soil carbon loss or sequestration

It assumed that these cattle production systems are not driving any significant land use change (grazing is extensive on natural pastures and utilisation of crops is generally in the form of crop residues from local food crops); therefore they are assumed to exist in soil carbon equilibrium. Research in the Senegal study locations has demonstrated some potential for soil carbon sequestration through improved agricultural practices, with varying cost-effectiveness (Tschakert, 2004). If mitigation measures for the study systems had included improvement to crop systems that the livestock systems have some reliance on, soil carbon sequestration consideration would have been required. It is also important to note it would become more important should production systems intensify significantly and reliance on crops grown specifically for animal feed.

5.3. Modelling the application of mitigation measures

5.3.1. Model changes to represent mitigation measure application

GLEAM input parameters for baseline study systems were altered to represent the expected changes to the systems when each mitigation measure is applied; these parameter changes are detailed in Table 5.6. (for animal health) and Table 5.7. (for feed and nutrition).

Table 5.6. Changes made to model input parameters to represent the expected productivity changes when disease burdens are removed from the Senegal study populations.

Disease	**Milk yield (%)**	**Body weight (%)**	**Death rate (%)**						**Fertility rate (%)**
			birth	**female 0-1**	**male 0-1**	**1-2**	**2-3**	**3+**	
LSD	1.9[a]	1.2[a]	-0.7[a]	-0.7[a]	-0.7[a]	-0.7[a]	-0.6[a]	-0.6[a]	7.1[b]
FMD	1.5[c]	2.1[c]	-0.6[c]	-0.6[c]	-0.6[c]	-0.4[c]	-0.3[c]	-0.3[c]	6.9[b]
Tryps	3.6[d]	0.6[d]	-8.7[d]	-9.4[d]	-7.9[d]	-12.5[d]	-10.0[d]	-14.3[d]	3.0[d]

LSD = Removal of Lumpy Skin Disease burden from the population;
FMD = Removal of Foot and Mouth Disease burden from the population;
Tryps = Removal of Trypanosomiasis burden from the population;
[a] Derived from: Daher (1994), Abutarbush *et al.* (2015), Ayelet *et al.* (2013), Hailu *et al.* (2015), Gari *et al.* (2011), Salib and Osman (2011), and assuming prevalence of LSD in the population of 7.1% (Ministère de l'élevage et des productions animales, 2014; Ministère de l'élevage, 2013).
[b] Assumed if animal had LSD or FMD it will be infertile, so fertility burden is equal to respective disease prevalence (Gari *et al.*, 2011; Knight-Jones and Rushton, 2013).
[c] Dervied from: Bayissa *et al.* (2011), Lyons *et al.* (2015), Rufael *et al.* (2008), Young *et al.* (2012), Şentürk and Yalçin (2008), Jemberu *et al.* (2014), Onono *et al.* (2013b), and assuming prevalence of FMD in the population of 6.9% (Ministère de l'élevage et des productions animales, 2014; Ministère de l'élevage, 2013).
[d] Taken from Shaw *et al.* (2006), and assuming that 50% of Senegal study herds are in regions with the tsetse fly (Bouyer *et al.*, 2010; Seck *et al.*, 2010).

Table 5.7. Details of changes made to model input parameters when feed related mitigation measures are applied to ‘baseline’ systems. At this stage there are no changes to productivity model input parameters (e.g. milk yields and body weights) when nutritional mitigation measures are applied.

Mitigation measure	Model input parameter change	Other changes
GNC +5%	GNC portion of total ration increased by 5%	Other ration components are reduced in quantity, but remain *pro rata*
GNC CP13/15/17%	GNC portion increased until ration crude protein content is 13%/15%/17%[a]	
PC 30%	PC portion increased to be 30% of total ration[a]	
PC 40%	PC portion increased to be 40% of total ration	
PC +5%/+10%	PC portion of total ration increased by 5% or 10%	
Hay	Hay digestibility improved from: ‘baseline’ (46.6 DE%[b]) to ‘optimal’ (50 DE%[b]); this includes nutritional value losses when hay is stored[c]	Ration component proportions remain unchanged
Urea treatment	Crop stover nutritional value improved from: ‘baseline’ (33.2 DE%[b], 9.6 gN/kg[b]) to ‘treated’ (42.8 DE%[d], 21.7 gN/kg[d])	
Cowpea	Cowpea forage (58.4 DE%[e], 27.4 gN/kg[e]) replaces other conserved or collected forages in baseline rations (stovers, hay, cut & carry pasture; average 45.0 DE%, 13.2 gN/kg)	

GNC = groundnut cake; PC = purchased compound feed; DE% = ration digestibility (expressed as percentage of gross energy); gN/kg/DM = grams of nitrogen per kg of dry matter

[a] As advised in Lukuyu *et al.* (2012)

[b] Based on data in Jarrige (1989)

[c] Based on Feyissa *et al.* (2014)

[d] See Chenost and Kayouli (1997)

[e] Feedipedia (www.feedipedia.org)

Parameter changes for animal health mitigation measures (Table 5.6.) were based on available literature detailing the productivity burden imposed on cattle by the shortlisted diseases (as referenced in Table 5.6. footnotes). This methodology has been employed by previous studies investigating the productivity burdens of key cattle diseases in SSA (Shaw *et al.,* 2006). Parameter changes for nutritional mitigation measures are also based on available literature directing the effective feeding of cattle in SSA (for example Lukuyu *et al.* (2012)). For certain measures

(GNC and PC) those herd types that have a higher productivity or production potential (Section 2.2.) will have mitigation measures enacted to a greater level. For instance, GNC will be increased until crude protein content of the total ration is at 13% for lower productivity herds, but until crude protein content of the total ration is at 15% or 17% for higher productivity herds. In addition, if purchased compound feed is at 30% or higher in current rations, it will be increased to 40%.

In the first instance measures were applied stand-alone, assuming no interaction between measures and comparing Ei always to the baseline systems to suggest abatement potential. Abatement potential (tonnes of CO_2eq abated per herd per year) was calculated by multiplying the difference in Ei between 'baseline' and 'mitigation measure applied' scenarios, by the 'baseline' scenario protein yield. This assumes that emissions can be reduced by producing the same amount of protein more efficiently with regards to GHG emissions.

The cost of implementing each mitigation measure is the change in herd gross margin arising from the implementation of the measure (calculated for typical herds, with eight breeding cows and following young stock and bulls, on an annual basis). The cost-effectiveness of applying each mitigation measure was calculated by dividing the cost of implementing the mitigation measure by the abatement potential (see Equation 5.1.). Only the private costs of implementation were considered. Individual households do not incur the cost of tsetse removal, to remove the burden of Tryps, as it is part of a regional Senegal Government project (Bouyer *et al.*, 2014). However, a relative cost to individual households is included to allow effective comparison with other measures. Social costs (e.g. economic welfare, environmental impacts beyond GHGs, human health and animal welfare) would require further quantification to be included in the analysis.

Equation 5.1

$$\frac{CE}{(\$/tCO_2eq)} = \frac{Gross\ margin\ with\ measure\ applied -\ Gross\ margin\ without\ measure\ applied}{(Ei\ with\ measure - Ei\ without\ measure) \times Baseline\ protein\ yield}$$

5.3.2. Cost assumptions

Revenue and cost assumptions for study systems are detailed in Appendix D. The cost of implementing feed related mitigation measures represents an annual recurring cost to maintain an improved ration. Based on the range of feed materials present in the baseline rations, it was assumed that no additional fixed costs or capital investments are required to improve feed rations and that any additional costs (e.g. transport) are included in the price of the feed materials (as suggested by SDG survey results). The cost of implementing measures to remove the burden of FMD and LSD also represent an annual recurring cost, with control based on the implementation of effective vaccination programmes. It was assumed that any additional costs are included in the price of the treatment (as suggested by SDG survey results). The costs of Tryps burden removal were based on the project within Senegal to remove the tsetse fly vector (Bouyer *et al.*, 2014). Due to the isolation of the tsetse fly population in Senegal from the rest of the African tsetse belt, an assumption was made that once the initial project cost of eradicating the tsetse fly is applied, the eradication will be sustainable without additional costs (as suggested by the project co-ordinators (Bouyer *et al.*, 2014)). Therefore, to consider the net present value, the costs and benefits of the tsetse vector eradication were discounted. A discount rate of 10%, suggested by Shaw *et al.* (2013) to be acceptable for livestock projects, was applied over 30 years.

5.3.3. Mitigation measures applied in isolation

The results of applying the mitigation measures in isolation to the baseline systems are shown in Table 5.8.; within the main text of the thesis results are displayed for herd types IZ and IZ x BT (as examples of two ends of a variety of systems), results for other herd types are in Appendix E. The abatement potential and cost-effectiveness of mitigation measures will be discussed after interactions between mitigation measures have been recognised and included in the following section.

Table 5.8. GLEAM results for mitigation measures (MM) applied in isolation (assuming no interaction between measures). Abatement potential (AP) (tCO_2e/herd/year) and cost-effectiveness (CE) (\$/tCO_2e) of MM are presented in order of CE.

	IZ	
	+	
MM	**AP**	**CE**
FMD	1.9	-79.0
LSD	2.1	-77.6
Hay	0.2	-14.4
Tryps	1.8	-10.0
Urea	0.9	34.3
Cowpea	5.3	67.5
GNC +5%	2.3	173.2
GNC CP13%	2.3	173.4
PC 30%	1.8	1370.0
PC +5%	0.4	1404.0

	IZ	
	++	
MM	**AP**	**CE**
FMD	1.7	-138.5
LSD	2.0	-133.3
Hay	0.6	-34.4
Tryps	1.7	-26.3
Urea	0.8	6.8
Cowpea	5.8	110.2
GNC +5%	2.3	178.3
GNC CP13%	1.1	203.8
PC 30%	1.3	1884.0
PC +5%	0.3	1950.1

	IZ x BT	
	++	
MM	**AP**	**CE**
FMD	1.5	-218.1
LSD	1.8	-197.7
Tryps	1.4	-53.5
Hay	0.8	-36.4
Urea	0.5	1.2
Cowpea	4.4	138.6
GNC +5%	1.9	176.2
GNC CP15%	1.6	177.7
PC 40%	0.6	4600.4
PC +10%	0.2	5203.6

	IZ x BT	
	+++	
MM	**AP**	**CE**
FMD	1.5	-408.7
LSD	2.0	-356.6
Tryps	1.6	-99.1
Urea	0.3	-53.8
Hay	1.7	-53.7
GNC +5%	2.4	142.8
GNC CP15%	2.8	166.8
Cowpea	4.6	243.0
PC 40%	-0.1	

FMD: Remove the burden of Foot and Mouth Disease
LSD: Remove the burden of Lumpy Skin Disease
Hay: Improved nutritional value of hay through optimal timing of harvesting
Tryps: Remove the burden on Trypanosomiasis
Urea: Urea treat crop stovers
Cowpea: Replace current forages in baseline rations with cowpea forage
GNC +5%: Increase the groundnut cake proportion of the baseline ration by 5%
GNC 13/15/17CP%: Increase the groundnut cake proportion of the baseline ration until total ration crude protein equals 13/15/17% (dependent on current ration composition, herd productivity and productivity potential)
PC 30/40%: Increase the purchased concentrate (compound) feed proportion of the baseline ration so it composes 30/40% of total ration (dependent on current ration composition, herd productivity and productivity potential)
PC +5/10%: Increase the purchased concentrate (compound) feed proportion of the baseline ration by 5/10% (dependent on current ration composition, herd productivity and productivity potential)

5.3.4. Mitigation measures applied as packages

In reality mitigation measures are likely to be adopted as packages and applied simultaneously. When measures are applied together there are likely to be interactions between them causing changes to both the abatement potential and cost-effectiveness of application (Moran *et al.*, 2011). Following the assessment of the cost-effectiveness of measures with no interaction (Table 5.8.), measures were applied as packages (in an order defined by the cost-effectiveness when applied in isolation) with interactions between them considered:

- To reflect interactions between feed related measures, the values for GNC, PC, Hay, Urea treatment and Cowpea were recalculated after the implementation of each measure.
- Certain feed related measures cannot be applied simultaneously, either they act on the same portion of the ration (i.e. urea treatment of crop stovers and cowpea forage replacing poorer forages, including crop stovers) or are different variants of the same measure (i.e. groundnut cake and purchased concentrate adjusted in different ways). Whichever is more cost-effective when applied in isolation is selected in the package of mitigation measures.
- For animal health measures it was assumed that burdens for each disease would be removed from different animals in the herd (i.e. that there were no interactions between these measures). Based on the prevalence of the diseases, the portion of the herd that could be burdened by more than one disease was calculated, for this portion productivity (e.g. milk yields) were only increased once by the first disease removal (FMD, as it was most cost-effective).

Abatement potential was calculated by multiplying the difference in Ei of the system with the measure being considered and without the measure being considered, by the 'baseline' system protein yield. The results of applying packages of mitigation measures to the baseline study systems are shown in Table 5.9.. One tonne of CO_2eq is equal to approximately 2% of total herd GHG emissions.

Table 5.9. GLEAM results for mitigation measures (MM) applied as packages (considering interaction between measures). Abatement potential (AP) (tCO_2e/herd/year) and cost-effectiveness (CE) ($\$/tCO_2e$) of MM are presented in order of application to the systems (order defined by CE when measures were applied in isolation)

IZ			IZ		
+			++		
MM	**AP**	**CE**	**MM**	**AP**	**CE**
FMD	1.9	-79.0	FMD	1.7	-138.5
LSD	1.8	-92.0	LSD	1.7	-155.9
Hay	0.2	-18.0	Hay	0.5	-42.4
Tryps	1.3	-11.7	Tryps	1.2	-34.4
Urea	0.9	38.9	Urea	0.9	8.7
GNC +5%	1.8	245.9	GNC +5%	1.9	255.2
PC 30%	0.5	5393.4	PC 30%	0.2	13357.5

IZ x BT			IZ x BT		
++			+++		
MM	**AP**	**CE**	**MM**	**AP**	**CE**
FMD	1.5	-218.1	FMD	1.5	-408.7
LSD	1.5	-231.0	LSD	1.7	-412.7
Tryps	1.0	-69.7	Tryps	1.2	-130.1
Hay	0.7	-47.9	Urea	0.3	-57.4
Urea	0.5	3.5	Hay	1.6	-70.1
GNC +5%	1.5	254.0	GNC +5%	2.0	212.5
PC 40%	-0.6		PC 40%	-1.4	

FMD: Remove the burden of Foot and Mouth Disease
LSD: Remove the burden of Lumpy Skin Disease
Hay: Improved nutritional value of hay through optimal timing of harvesting
Tryps: Remove the burden on Trypanosomiasis
Urea: Urea treat crop stovers
GNC +5%: Increase the groundnut cake proportion of the baseline ration by 5%
PC 30/40%: Increase the purchased concentrate (compound) feed proportion of the baseline ration so it composes 30/40% of total ration (dependent on current ration composition, herd productivity and productivity potential)

The effective control through vaccination of FMD and LSD, and the removal of Tryps burden through tsetse vector control, are consistent 'win-win' interventions. Productivity improvements reduce the Ei of protein, reducing total emissions; whilst the cost of additional vaccination for effective protection is assumed to be outweighed by the expected increases in household revenue (from increased milk yields and carcass weights). The removal of Tryps burden through the project explained by Bouyer *et al.* (2014), has an initial project cost, but then is followed by reoccurring annual productivity benefits. Discounting the household revenue benefits over a period of 30 years provides a net present value that outweighs the project costs. A further refinement could be to allocate some of the cost to other benefits of removing the tsetse vector, such as expected health and production benefits for other livestock species and a reduction in grazing pressure (Bouyer *et al.*, 2014); this may increase the cost-effectiveness of tsetse removal further. The herd level productivity burdens (Table 5.6.) of these shortlisted diseases are based on disease prevalence records, and are likely to be underestimated as disease occurrence is commonly under-reported (Tebug *et al.*, 2015).

The improved timing of hay harvesting for optimal nutritional value is also suggested as a 'win-win' option. The improved nutritional value of hay improves the overall quality of the ration, and means less ration is required to meet the energy requirements of the cattle, representing reduced emissions and a cost reduction. It is assumed that improved hay will not increase in cost and will not require any additional labour. The cost-effectiveness, although always below \$0/tCO_2eq, varies between systems depending on the proportion of hay in the ration. The Zebu Taurine cross (IZ x BT) and Taurine (BT) herds spend more time housed, so hay is a larger proportion of their ration (30% and 18% respectively); therefore, this measure is most cost-effective when applied to these systems. Both Zebu Taurine cross (IZ x BT) with a higher level of management and Taurine (BT) herds have a higher proportion of millet stover in their ration, making the urea treatment of stover a 'win-win' measure for these systems only. Groundnut cake and purchased compound feed, although highly digestible, are costly and have greater lifecycle emissions than the other feed material options (Hay, Urea treatment etc.). In the current method animal performance is not improved feed related measures are applied, therefore their abatement potentials are low, or even increase absolute emissions, and are costly. Figure 5.5. shows a marginal abatement cost curve (MACC) (Box 5.1.) for the package of mitigation measures applied to typical herds (with eight adult cows), of indigenous Zebu with a lower level of management input (IZ +), and of indigenous Zebu Taurine cross with a higher level of management input (IZ x BT +++).

Box 5.1. Marginal Abatement Cost Curves

A Marginal Abatement Cost Curve (MACC) offers a graphical illustration of the abatement potential and costs associated with GHG mitigation measures, a hypothetical example is shown in Figure 5.4.. The construction of MACCs for agriculture is increasingly common (Macleod *et al.*, 2010; Moran *et al.*, 2011; Pellerin *et al.*, 2013; Schulte *et al.*, 2012). MACCs illustrate several elements of information:

a) The cost-effectiveness of mitigation measures, by which the measures are ordered along the x-axis. Measures can be: cost-saving (reduce GHG emissions and save money), cost-neutral (reduce GHG emissions and have zero net cost), economically-efficient (reduce GHG emissions with a cost less than the cost of carbon), or economically-inefficient (reduce GHG emissions with a cost higher than the cost of carbon)

b) The GHG emission abatement potential of mitigation measures (the width of the bars on the x-axis)

c) The total cost of each mitigation measure, equal to the area of each respective bar

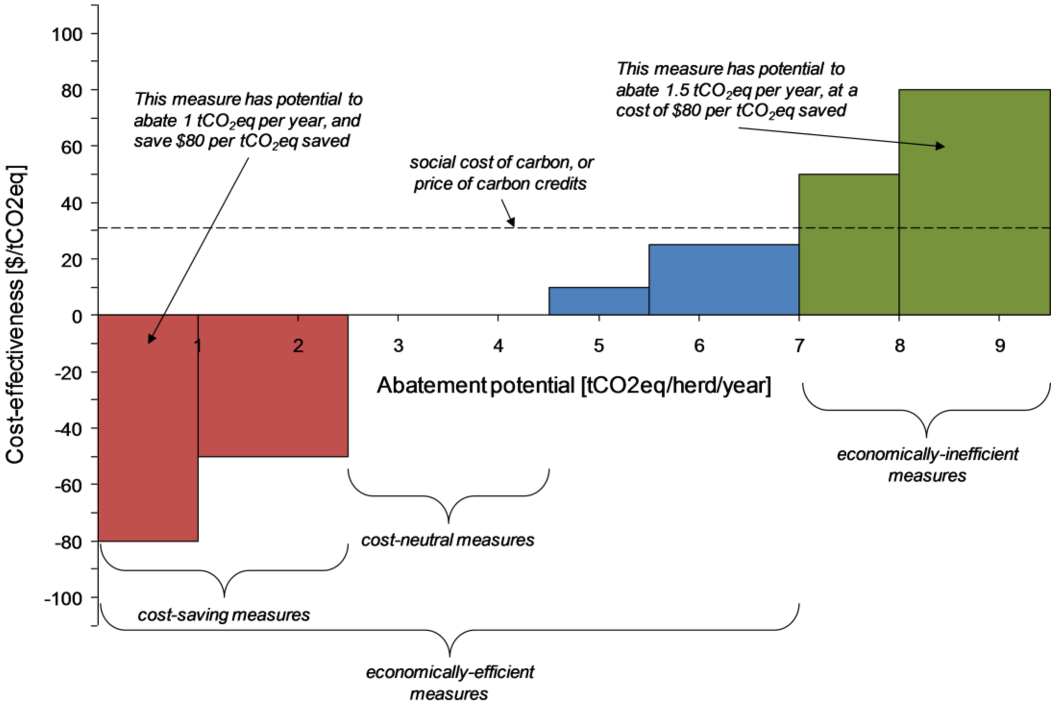


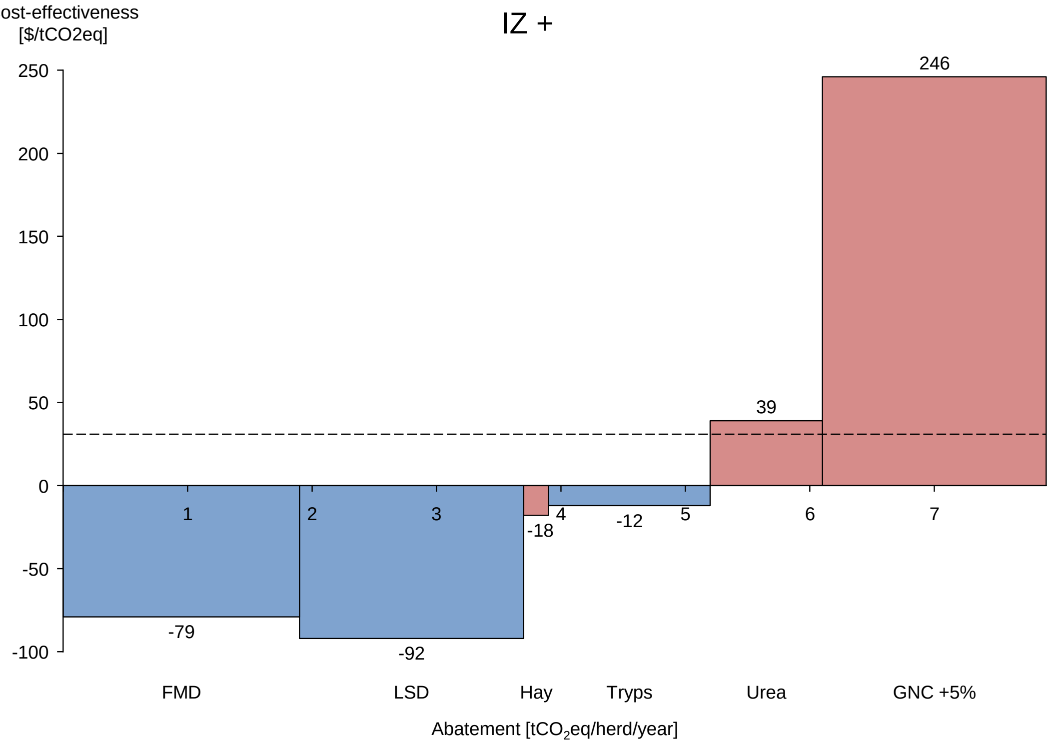
Figure 5.4. Example Marginal Abatement Cost Curve (MACC) with element explanation

Figure 5.4. proposes 2.5, tCO$_2$eq could be abated through cost-saving measures; and a total of 7 tCO$_2$eq could be abated through economically-efficient measures.

MACCs provide a useful tool to illustrate and compare the cost-effectiveness of mitigation measures, however they should be ‘just one tool in a broader set of decision-making aids’ (Kesicki and Ekins, 2012).

Figure 5.5. demonstrates the usefulness of MACCs as tools for comparing the cost-effectiveness of mitigation measures for different scenarios. Several comments can be made when considering the two MACCs:

- For health related measures (FMD, LSD, Tryps) the abatement potential is greater for the higher productivity herd (IZ x BT +++), this is likely due to greater increases in total amount of production. However, the higher productivity herd (IZ x BT +++) abatement potential is limited to a greater extent than the low productivity herd (IZ +), as increases in feed intake and lifecycle emissions associated with the feed will be greater.
- Cost-saving for the health related measures is greatest for the higher productivity herd (IZ x BT +++), greater increases in the total amount of production will incur greater increases in household revenue.
- The abatement potential of hay improvement and urea treatment of crop stovers is dependent on the portion of the baseline rations these account for, as discussed above.
- The cost-effectiveness of feed related measures is dependent on each measures impact on total feed requirement (as productivity is currently not changed when feed related measures are applied). The higher productivity herd (IZ x BT +++) has a more costly ration, so when measures increase the nutritional value of the total ration and reduce intake requirements these herds have a greater cost saving, than the low productivity herd with cheaper baseline rations (IZ +).
- The cost-effectiveness of urea treatment of crop stovers for the IZ + herd type (39 $/tCO$_2$eq) is close to the social cost of carbon reference line ($31/tCO$_2$eq); suggesting, that although there aren't private benefits to the livestock keepers, this measure may be cost-efficient for society as a whole.



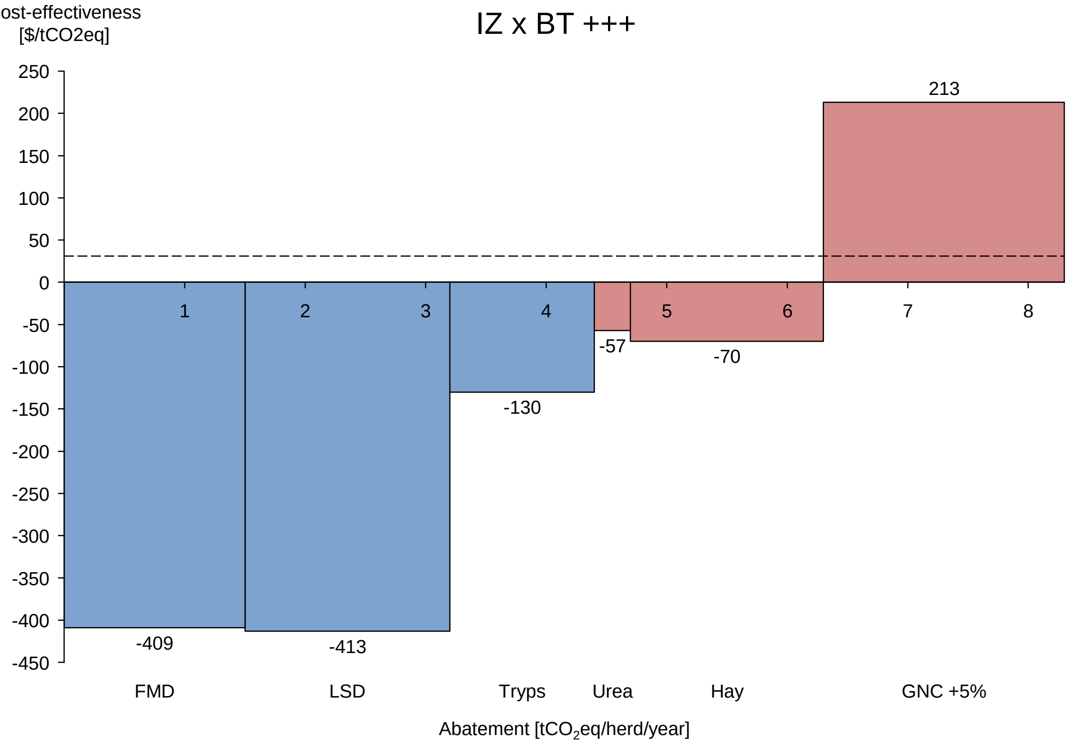


Figure 5.5. Annual Marginal Abatement Cost Curves (MACC) for typical herds, of IZ + (top) and IZ x BT +++ (bottom). Measures are applied packages in order from left to right, with interaction between measures considered. Dashed reference line illustrates a social cost of carbon of $31/tCO_2eq$. Measures appear to not be applied in order of cost-effectiveness; they are applied in an order defined by their CE when modelled in isolation. See Table 5.9. for measure definitions.

5.4. Limitations to the modelling of feed related mitigation measures

By altering model input parameters to simulate the application of mitigation measures onto baseline systems, GLEAM V1.0 enables the quantification of GHG emission abatement potential. For animal health related mitigation measures productivity related model input parameters are altered to simulate the removal of disease burdens. However, in the current method for feed related mitigation measures there is no change to productivity related model input parameters (i.e. milk yields, body weights etc.).

As ration digestibility is improved two variables change in the model. First, the ratio of net energy available in the ration for both maintenance (REM) and growth (REG) to digestible energy consumed increases. As no productivity increases are included in the model for nutritional improvements, the net energy requirements do not change and the animals' gross energy requirement decreases (Figure 5.6.). For each unit of feed consumed more net energy is available. Subsequently, there is a decrease in both feed intake and the associated emissions. Secondly, with increasing ration digestibility the percentage of gross energy consumed converted to CH_4 by enteric fermentation decreases, and as gross energy required has decreased as does the quantity of enteric CH_4 produced (Figure 5.7.).

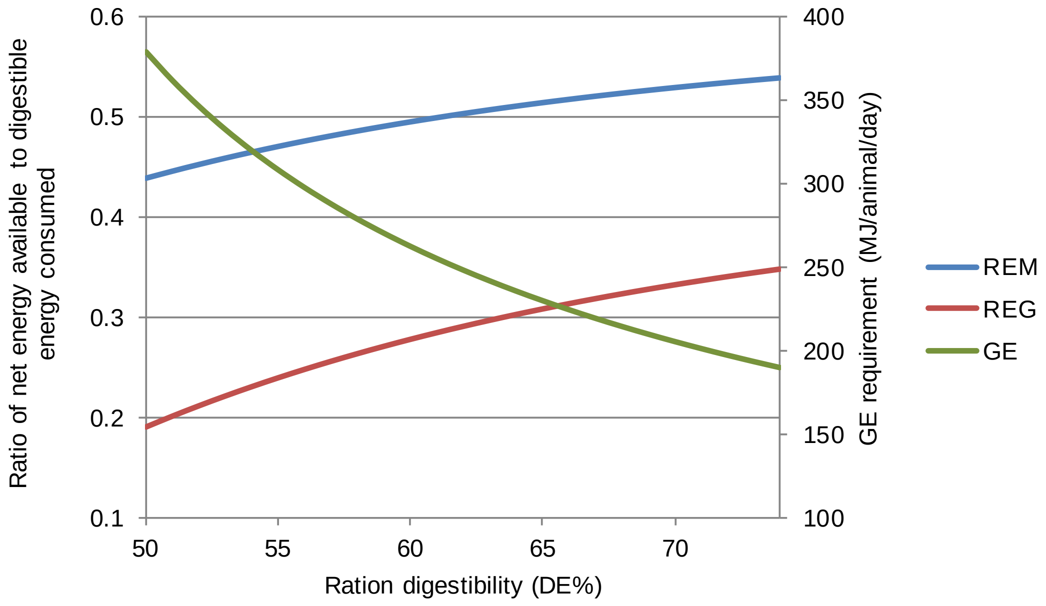


Figure 5.6. The response to increased ration digestibility (DE%: digestible energy as a percentage of gross energy) of the ratio of net energy available to digestible energy consumed, for both maintenance (REM) and growth (REG), and gross energy requirement (GE). Assuming constant net energy requirements.

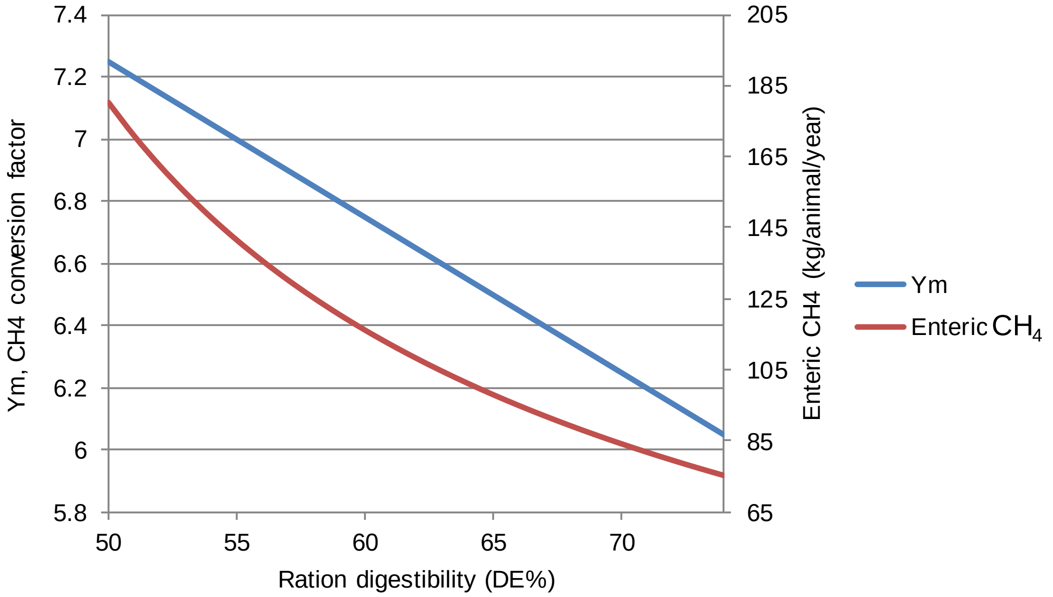


Figure 5.7. The response to increased ration digestibility (DE%: digestible energy as a percentage of gross energy) of the CH_4 conversion factor (Ym, percentage of gross energy in feed converted to CH_4) and enteric CH_4. Assuming constant net energy requirements.

Therefore, the emissions abatement potential and cost-effectiveness of the nutritional mitigation measures are derived from both reduced feed intake requirements and reduced enteric CH_4 emissions. Neither of these responses to increasing ration digestibility are linear, instead they follow curves of diminishing returns and abatement potential is dependent on the baseline ration digestibility from which improvements are made (i.e. where on the curves the baseline ration digestibility is) (Figure 5.6. and Figure 5.7.). Nutritional measures applied to low digestibility baseline rations have more abatement potential than those same measures applied to higher digestibility baseline rations; likewise when measures are applied as packages nutritional measures that follow the application of previous nutritional measures will have less abatement potential than if they were applied in isolation. If we consider the application of PC 40% in isolation (increasing purchased compound feed in the ration until it accounts for 40% of the total ration), for IZ x BT +++ herds, the starting baseline ration digestibility is higher than most other herd types (Table 5.2.). Therefore, the abatement potential of the measure is not great enough to outweigh the emissions associated with the lifecycle of the increased proportion of PC in the ration, Ei increases and abatement potential is shown as negative (Table 5.8.). Then if we consider the same mitigation measure but as part of a package of measures, the feed ration digestibility has already been increased by previously applied nutritional measures, therefore the abatement potential of the PC 40% measure is further reduced and the emissions increase is greater.

Evidently, there is a key limitation to the assessment of feed related mitigation measures when using the Tier 2 methodology in its current form. In reality when a ration is improved, feed intake and animal productivity would likely increase (e.g. higher milk yields, greater body weights and faster growth), this is particularly pertinent for systems likely to be nutritionally limited (Ayenew *et al.*, 2009; Bryan *et al.*, 2013).

The emissions abatement potential and cost-effectiveness of feed related mitigation measures would then be a balance between:

a) productivity improvements, increasing both household revenue and units of produce over which to allocate emissions (reducing Ei); and
b) an increase in energy requirement and feed intake, increasing emissions associated with feed and increasing the household feed costs.

It is evident that the estimation of productivity response when rations are improved is important to the balance of production GHG emissions efficiency, particularly for these study systems where cattle are likely to be limited by poor nutrition. Chapter six further discusses this challenge and explains a methodology towards overcoming this challenge and discusses the effect this has on Ei results.

CHAPTER SIX

ANIMAL PRODUCTION RESPONSE TO IMPROVED FEED AND NUTRITION

6.1. Recognising a key limitation when employing the Tier 2 approach

As discussed in previous chapters, cattle production is recognised as being a significant source of global GHG emissions (Gerber *et al.*, 2013b). However, it has also been suggested that cattle production systems offer opportunities to reduce emissions; particularly through improving productivity and reducing Ei of production in developing regions (Gerber *et al.*, 2011, 2013a). This emission abatement potential can be quantified using carbon foot-printing tools; which commonly use a Tier 2 approach to determine the emissions associated with production (Sykes *et al.*, 2017). In this method the physical production performance of cattle and the composition of the ration are exogenous (separate inputs) and therefore independent. In reality, some aspects of cattle performance (such as milk yields and growth rates) are dependent on ration composition (Manninen *et al.*, 2011). Therefore, the absence of any link between performance and ration composition within models could lead to misleading results and limits the utility of the Tier 2 approach in quantifying the abatement potential of feed related mitigation measures. Ideally, ration composition and animal performance would be linked within Tier 2 models, ensuring consistency and transparency; Table 6.1. summarises some studies that have attempted this.

Table 6.1. Summary of relationships between ration composition and animal performance used by previous studies. Both studies are based on Tier 2 IPCC methodologies.

Authors	Scenarios modelled	Link between ration composition and animal performance	Assumption basis
Gerber *et al.* (2013b)	Feed quality improvement for South Asian dairy production Pasture quality improvement for South American beef production Forage quality improvements for West African small ruminants	1% increase in diet digestibility assumed to increase: growth rate by 4% milk yield by 4.5% to 5%	Experimental studies in literature[a]
Eory *et al.* (2015)	Nutrition improvement for beef and sheep in the UK	2% increase in diet digestibility assumed to increase growth rates by 2%	Literature review of experimental results[b]

[a] Based on Keady *et al.* (2012), Steen *et al.* (1987), Manninen *et al.* (2011), Scollan *et al.* (2001), and Bertelsen *et al.* (1993)
[b] See Hristov *et al.* (2013)

6.2. Models that do link feed rations to animal production

A variety of models exist that have been developed to consider links between ruminant production, and ration composition and quantity (Tedeschi *et al.*, 2005). Generally, for a predicted or expected yield (e.g. milk offtake or carcass weight) nutritional requirements are assessed and cost-effective rations proposed. Such models are commonly used by ruminant nutritionists; for example SAC Consulting's FeedByte software[8], which 'simulates the physical processes based on least cost diet formulation and linear programming modelling' (Chagunda *et al.*, 2010). However, these models do not predict yields from an entered ration; instead they suggest effective rations from an entered yield.

In contrast RUMINANT, an IPCC Tier 3 digestion and metabolism model, uses stoichiometric calculations (i.e. balancing equations) to estimate both cattle system

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[8] http://www.sruc.ac.uk/info/120110/dairy_services

inputs and outputs (Herrero *et al.*, 2013b). Two functional sections, 'nutrient supply' and the 'nutrient requirement', predict feed intake and digestibility, and nutrient requirements and performance respectively. This model bases evaluation of animal performance on the Cornell Net Carbohydrate and Protein System (CNCPS) rumen model (Tylutki *et al.*, 2007); which predicts situation specific requirements and nutrient supply for cattle production.

As descriptions of these models commonly recognise, the key challenge to calculating productivity responses to additional energy made available, is predicting how the animal will allocate energy to different physiological processes (CSIRO, 2007; Tylutki *et al.*, 2007)(Figure 6.1.).

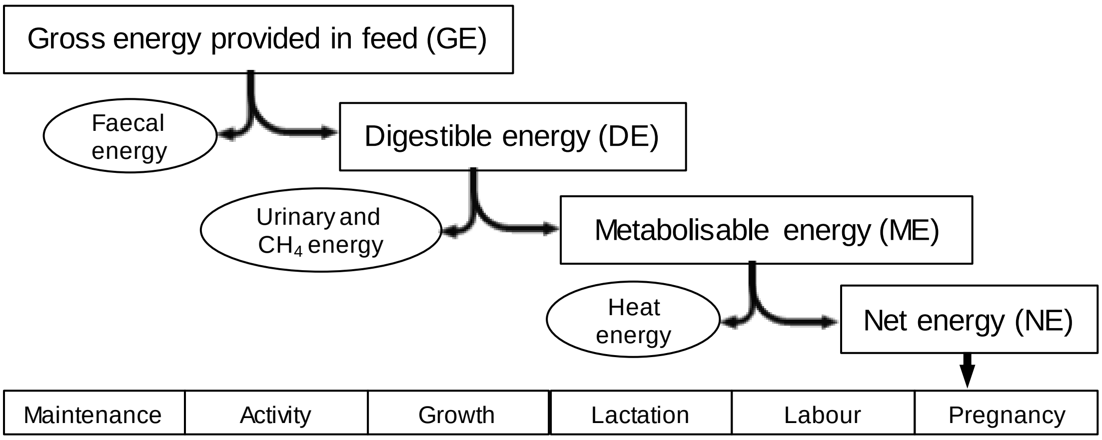

Figure 6.1. Demonstration of the potential allocation of gross energy provided to an animal in feed rations.

Proposed in the following sections is a simple model based on ration digestibility influencing energy availability, and assumptions of the allocation of additional energy to different physiological processes (steps are summarised in Figure 6.2. and discussed in more detail in Section 6.3.). It adapts the Tier 2 approach on which GLEAM V1.0 is based (IPCC, 2006) to allow calculation of animal performance response to improved rations, and to enable harmonisation within a version of GLEAM V1.0.

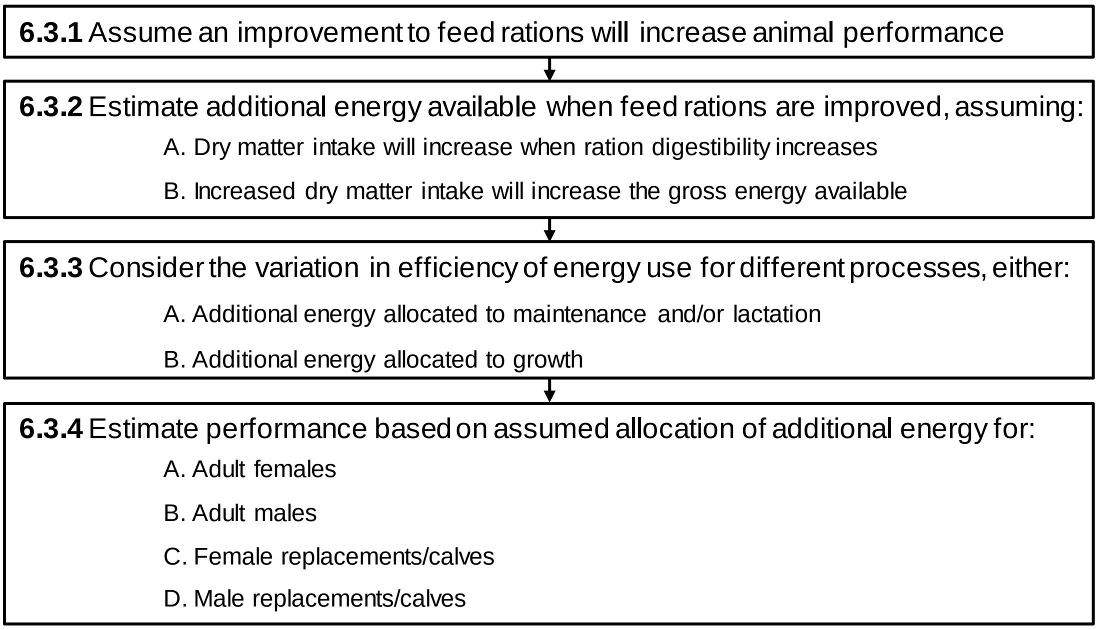

Figure 6.2. Summary of steps taken to estimate improvement to animal performance when ration composition is improved. Full details explained in the following sections.

6.3. Proposed animal production response addition to GLEAM methodology

6.3.1. Assume a feed improvement will increase animal performance

There is extensive evidence that cattle in developing regions are often undernourished, consequently they are unlikely to reach their full genetic potential for productivity (Ayenew *et al.*, 2009; Chagunda *et al.*, 2004; Garg *et al.*, 2013; Kahi *et al.*, 2000; Somda *et al.*, 2005). It can therefore be assumed that improving the nutritional value of feed rations, in particular energy digestibility, will lead to an increase in cattle productivity, as demonstrated by various studies (Bertelsen *et al.*, 1993; Manninen *et al.*, 2011; Scollan *et al.*, 2001).

The improvement of quality of feed, rather than quantity of current feed materials, is considered for two reasons:

a) The study system baseline rations are of low digestibility (55 – 63 DE%), but feed ingredients are available to improve the ration nutritional value (e.g. groundnut cake and purchased compound feed).

b) The SDG questionnaires revealed that around half of the study households had experienced livestock feed shortages in the previous five years. When shortages were experienced they used conserved natural pasture (hay), understood to be readily available, but of poor quality, to fulfil rations.

Therefore, it is assumed that improving the quality of feed rations will increase both nutritional value and intake.

Only the energy function of feed rations is considered in the proposed methodology, this is due to two key reasons:

a) To harmonise the proposed methodology with the GLEAM V1.0 Tier 2 approach; which is also largely based on energy expenditure by livestock.
b) The requirement to simplify complex biological processes to allow modelling.

In making this decision it is important to highlight that feed has other purposes (Dryden, 2008), which are summarised in Table 6.2.; but are not currently included in this methodology. Therefore, certain restrictions to animal performance and benefits when making ration improvements are inevitably excluded.

Table 6.2. Summary of nutrient groups and functions (adapted from Dryden, 2008)

Nutrient group	Form in food	Functions
Amino acids	Protein	Synthesis of tissues, enzymes and hormones Surplus amino acids yield energy
Fatty acids	Fats	Synthesis of cell membranes and steroid hormones Yield energy
Carbohydrates	Starch, monosaccharides, and disaccharides	Forms glycoprotein or glycolipid Yield energy
Minerals	Organic and inorganic matter	Mineralisation of bone Enzyme cofactor
Vitamins	Active vitamins or pro-vitamins	Enzyme cofactor Gene expression
Water	Free water, water of crystallisation	Major constituent of tissue, blood and milk Medium in which reactions take place

6.3.2. Estimate additional energy available when feed is improved

A. Increased dry matter intake when ration digestibility is increased

It is likely that a change in digestibility will influence the rate of passage of feed through the rumen, and therefore have an effect on the rate of feed intake (CSIRO, 2007). Therefore, it is suggested that feed digestibility can be used to predict the rate of dry matter intake (DMI) (Freer and Jones, 1984). However, determining this relationship has been highly variable, with both positive and negative correlations (Minson, 1990; Moore and Coleman, 2001). To enable prediction of expected productivity improvements it is assumed, in this instance, that increasing digestibility will increase feed DMI (NRC, 2001). Studies have shown this to be particularly relevant in systems understood to be nutritionally limited (Ajayi *et al.*, 2005). DMI can be estimated from the digestibly of feed (DE%, digestible energy as a percentage of gross energy (GE)) using Equation 6.1.. This equation is used to calculate the increase in DMI that an improvement in feed ration DE% is likely to cause.

It is important to recognise this is a reverse of a causal chain in GLEAM V1.0 used in Chapter five; where DMI was based on energy requirements and the efficiency of energy use from feed consumed. Increasing the ration DE% increased the efficiency of energy use so less GE is required and therefore DMI is reduced. However, with the proposed approach an increasing ration DE% results in an increased DMI, as we assume animals to be undernourished and not likely at full production potential; this is further discussed in Section 6.5.

Equation 6.1. (10.18b IPCC, 2006, p.10.22):

$$DMI = \left[\frac{\left(\frac{(5.4 \times BW)}{500} \right)}{\left(\frac{(100 - DE\%)}{100} \right)} \right]$$

Where:

DMI = dry matter intake (kg day^{-1})

BW = live body weight (kg)

DE% = digestible energy as a percentage of gross energy

B. Additional gross energy available due to increased feed intake

The total additional GE available to animals, following an assumed increase in feed intake (DMI), will depend on the energy density of the feed. The Tier 2 methodology within GLEAM V1.0 assumed an average feed density of 18.45 MJ kg^{-1} (Opio *et al.*, 2013). However, the proposed methodology uses a more accurate feed density, dependent on the specific composition of the feed ration. This allows the model to take into account improvements to both the digestibility and energy density of feed rations. The additional GE available to the animal due to improved feed rations can be calculated using Equation 6.2.

Equation 6.2.:

$$Additional\ GE\ (MJ\ day^{-1}) = \\ Additional\ DMI\ (kg\ day^{-1}) \times Improved\ energy\ density\ of\ feed\ ration\ (MJ\ kg^{-1})$$

Considering Equation 6.1 and Equation 6.2, the same increase in feed ration digestibility (DE%) will result in different levels of additional GE for animals of different body weights. The greater the body weight, the greater the additional feed intake and additional GE (Figure 6.3.).

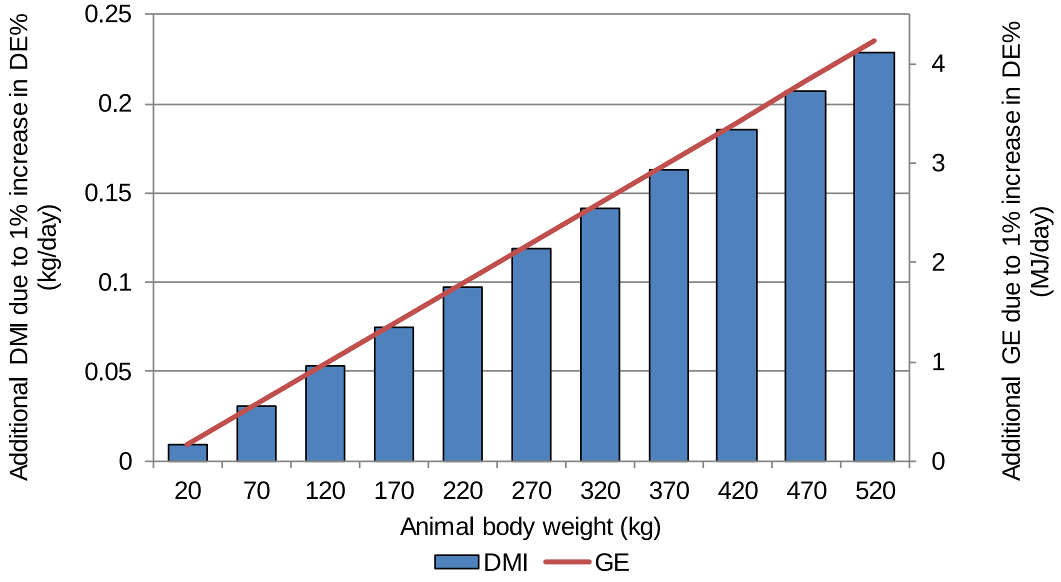

Figure 6.3. Demonstration of the assumed relationship (when using Equation 6.1) between body weight and additional daily feed intake (DMI) and gross energy (GE) available to animals when ration digestibility is increased by a 1%.

6.3.3. Variation in the efficiency of energy use for different processes

Following the estimation of additional GE available to the animal due to an increase in ration digestibility, net energy (NE) available for physiological processes is calculated. The NE available will vary depending on its allocation by the animal, as energy is used with different efficiencies for different physiological processes; it is suggested that energy will be most efficiently used for maintenance or lactation and then growth (CSIRO, 2007). This requires calculation of the 'ratio of net energy available in a diet for maintenance to digestible energy consumed' (REM) and the 'ratio of net energy available for growth in a diet to digestible energy consumed' (REG), using Equation 6.3. and Equation 6.4..

Equation 6.3. (10.14 IPCC, 2006, p.10.20):

$$REM = \left[1.123 - [4.092 \times 10^{-3} \times DE\%] + [1.126 \times 10^{-5} \times (DE\%)^2] - \left(\frac{25.4}{DE\%}\right)\right]$$

Equation 6.4. (10.15 IPCC, 2006, p.10.20):

$$REG = \left[1.164 - [5.160 \times 10^{-3} \times DE\%] + [1.308 \times 10^{-5} \times (DE\%)^2] - \left(\frac{37.4}{DE\%}\right)\right]$$

Where: DE% = digestible energy as a percentage of gross energy

Following the calculation of REM and REG, the Tier 2 equation 10.16 (IPCC, 2006, p. 10.21) is rearranged to estimate the NE available for different physiological processes. This requires an assumption as to whether the additional GE will be allocated either, to maintenance and/or lactation (A) or growth (B). Energy allocation is further simplified by assuming no additional energy goes to activity or pregnancy.

Rearrangement of Tier 2 equation 10.16 (IPCC, 2006, p. 10.21)**:**

$$GE = \left[\frac{\left(\frac{NE_m + NE_l}{REM}\right) + \left(\frac{NE_g}{REG}\right)}{\frac{DE\%}{100}} \right]$$

A. Additional GE assumed to be allocated to maintenance and/or lactation:

In this instance, it is assumed no GE is allocated to growth, therefore:

$$NE_g = 0$$

$$\left(\frac{NE_g}{REG}\right) = 0$$

Equation 10.16 can be therefore written:

$$GE = \frac{\left(\frac{NE_m + NE_l}{REM}\right)}{\frac{DE\%}{100}}$$

A rearrangement gives:

Equation 6.5. (NE available for maintenance and/or lactation)**:**

$$NE_m + NE_l = REM \times \left[GE \times \left(\frac{DE\%}{100}\right) \right]$$

B. Additional energy assumed to be allocated to growth

In this instance, it is assumed no GE is allocated to maintenance and/or lactation, therefore:

$$NE_m + NE_l = 0$$

$$\left(\frac{NE_m + NE_l}{REM}\right) = 0$$

This time, Equation 10.16 can therefore be written:

$$GE = \frac{\left(\frac{NE_g}{REG}\right)}{\frac{DE\%}{100}}$$

A rearrangement gives:

Equation 6.6. (NE available for growth)**:**

$$NE_g = REG \times \left[GE \times \left(\frac{DE\%}{100}\right)\right]$$

Where:

GE = gross energy (MJ day^{-1})

NE_m = net energy for maintenance

NE_l = net energy for lactation

NE_g = net energy for growth

6.3.4. Estimate improved production performance

A. Adult females

It is assumed that the additional energy available when rations are improved will be allocated to different physiological processes depending on the breed of cattle (Jenet *et al.*, 2006). *Bos indicus*, or Zebu cattle, are evolutionarily adapted to exist in harsh environments. Therefore they are more likely to respond to improved nutrition by depositing body tissue, rather than increasing lactation; this body weight can then be mobilised when nutrition is again limiting (Jenet *et al.*, 2006, 2004). Whereas, *Bos taurus*, or Taurine cattle, have been commonly bred to maximise milk yields; meaning they are more likely to respond to improved nutrition by increasing milk production, rather than recovering body reserves (Jenet *et al.*, 2006, 2004). Therefore, adult females of predominantly Zebu breed genetics are assumed to allocate additional energy to the maintenance of additional body weight. The additional body weight that can be maintained is estimated by rearranging Tier 2 equation 10.3 to give Equation 6.7., and assuming the additional NE allows additional body weight to be maintained.

Rearrangement of Tier 2 equation 10.3 (IPCC, 2006, p.10.15)**:**

$$NE_m = Cf_i \times (Additional\ body\ weight)^{0.75}$$

Equation 6.7. (Additional body that can be maintained)**:**

$$Additional\ body\ weight\ (kg) = \left(\frac{NE_m}{Cf_i}\right)^{\frac{1}{0.75}}$$

Where:

NE_m = net energy required for maintenance (MJ day^{-1})

Cfi = coefficient (0.386 for lactating cows) (MJ day^{-1} kg^{-1})

Conversely, adult females with predominantly Taurine breed genetics are assumed to allocate additional energy to increasing milk yield. The additional milk yield is estimated by rearranging Tier 2 equation 10.8 to give Equation 6.8..

Rearrangement of Tier 2 equation 10.8 (IPCC, 2006, p.10.18)**:**

$$NE_l = Milk \times (1.47 + 0.40 \times Fat)$$

Equation 6.8. (Additional milk yield)**:**

$$Milk\ (kg) = \frac{NE_l}{(1.47 + 0.40 \times Fat)}$$

Where:

NE_l = net energy for lactation (MJ day^{-1})
Milk = amount of milk secreted (kg of milk day^{-1})
Fat = fat content of milk (% by weight)

For mixed breed adult females, energy is allocated between body weight increase and milk yield increase proportionally to their genetic mix. For example, for an adult female, approximately 50% Zebu and 50% Taurine, receiving 2 MJ day^{-1} additional GE, 1 MJ day^{-1} would be allocated to an increased body weight and 1 MJ day^{-1} would be allocated to an increased milk yield.

B. Adult males

Additional energy available to adult males, due to increased ration digestibility, is assumed to be allocated to an ability to maintain an increased body weight. The additional body weight is estimated using the rearrangement of Tier 2 equation 10.3 (IPCC, 2006, p. 10.15), as seen above for adult females of zebu breeds (Equation 6.7.).

C. Replacement females/female calves

Additional energy available to replacement females and female calves is assumed to be allocated to increasing daily weight gain. Additional NE available to the replacement females comes from both the improvement to the digestibility of the ration, and a suckled portion of the increased milk yield of adult females, for the period whilst replacements are still suckling. Increased daily weight gain is estimated by rearranging Tier 2 equation 10.6 to give Equation 6.9.:

Rearrangement of Tier 2 equation 10.6 (IPCC, 2006, p.10.17)**:**

$$NE_g = 22.02 \times \left(\frac{BW}{C \times MW}\right)^{0.75} \times WG^{1.097}$$

Equation 6.9. (Additional weight gain)**:**

$$WG = \left(\frac{\left(\frac{NE_g}{22.02}\right)}{\left(\frac{BW}{C \times MW}\right)^{0.75}}\right)^{\frac{1}{1.097}}$$

Where:

NE_g = net energy for growth (MJ day^{-1})
BW = average live body weight of animals in the population (kg)
C = a coefficient with value of 0.8 for females and 1.2 for bulls
MW = body weight of an adult female in moderate body condition (kg)
WG = average daily weight gain of animals in the population (kg day^{-1})

The increased daily weight gain will be expressed by a reduced age at first calving (AFC), with replacements reaching maturity earlier (Sawadogo *et al.*, 1999). A reduced AFC is calculated by considering the time it would take a replacement animal to reach mature weight with the increased daily weight gain of the improved scenario (Equation 6.10.).

Equation 6.10. (Reduced AFC)**:**

$$Reduced\ AFC\ (years) = \frac{(Baseline\ adult\ female\ weight - \ Calfbirth\ weight)}{WG\ with\ improved\ ration}$$

D. Replacement males/male calves

It is assumed that replacement males will also reach maturity earlier, due to additional energy available to them increasing daily weight gain. GLEAM V1.0 assumes that male age at maturity is equal to female AFC; therefore the age at maturity for replacement males in an improved scenario will be assumed equal to the reduced AFC calculated for replacement females (Equation 6.9. and Equation 6.10.).

6.4. Harmonising the proposed methodology with Tier 2 and GLEAM V1.0

The methodology above is suggested as it enables a simple model, based on Tier 2 equations, to be harmonised with the current Tier 2 functioning within GLEAM V1.0. Figure 6.4. summarises this modification. Based on the altered ration composition for improved scenarios, an increase in milk yields, body weights and growth rates will adjust appropriate productivity parameters, and ultimately influence the Ei result.

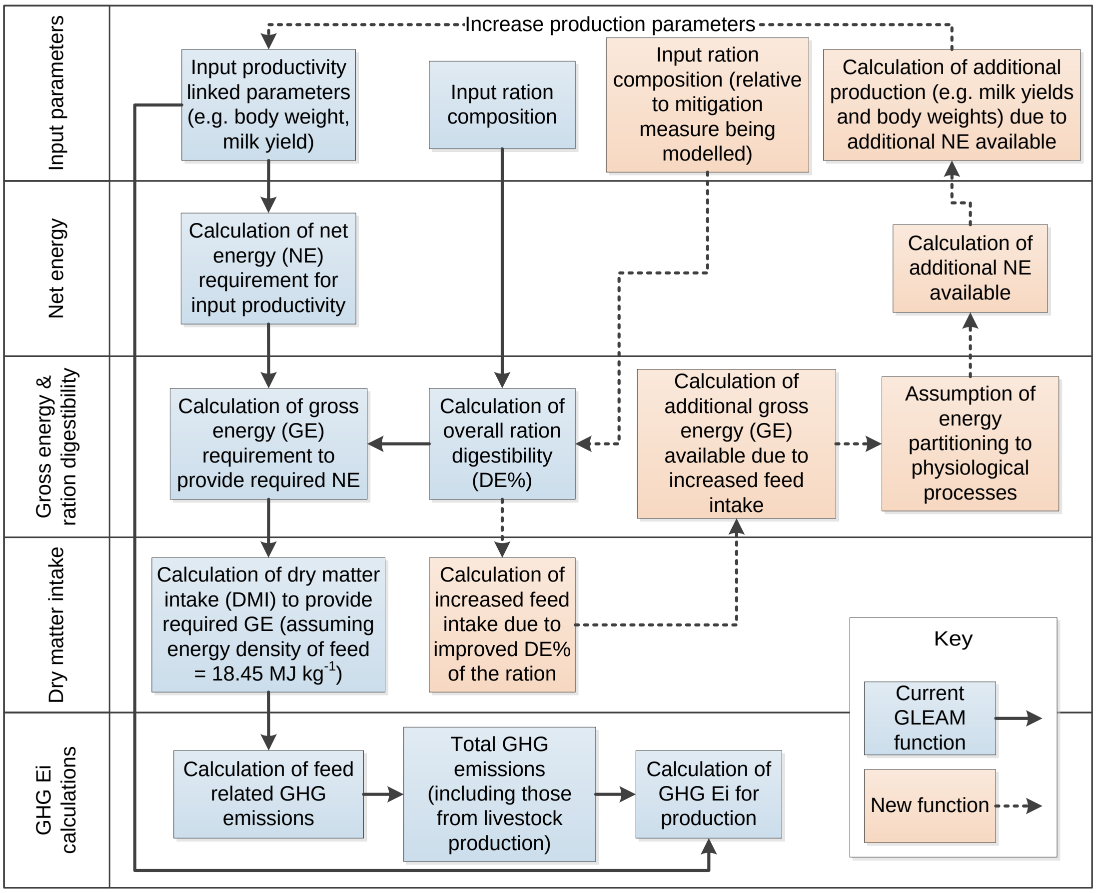

Figure 6.4. Summary of the harmonisation of the proposed methodology with GLEAM V1.0. It is important to note that any GLEAM scenario with improvement to ration digestibility will use a baseline scenario for comparison to allow estimation of animal performance improvement.

6.5. Contrast to modelling in Chapter five and consideration of uncertainty

In Chapter five feed related mitigation measures were applied to baseline scenarios, increasing ration digestibility. This saw an increase in the ratio of energy consumed to energy used for maintenance and growth (REM & REG, respectively). As discussed in Chapter five no productivity input parameters (e.g. milk yields, body weights or growth rates) were altered with the application of feed related mitigation measures. Therefore, with a constant NE requirement and the increasing efficiency of energy use, the GE requirement and feed intake needed decreased with increasing ration digestibility. These responses were not linear; instead they followed a diminishing rate of return (Figure 6.5.). An increase in ration digestibility from a lower baseline (e.g. DE% from 40% to 50%) saw a greater improvement to energy use efficiency and subsequent decrease in GE, compared to an increase in ration digestibility from a higher baseline (e.g. DE% from 50% to 60%).

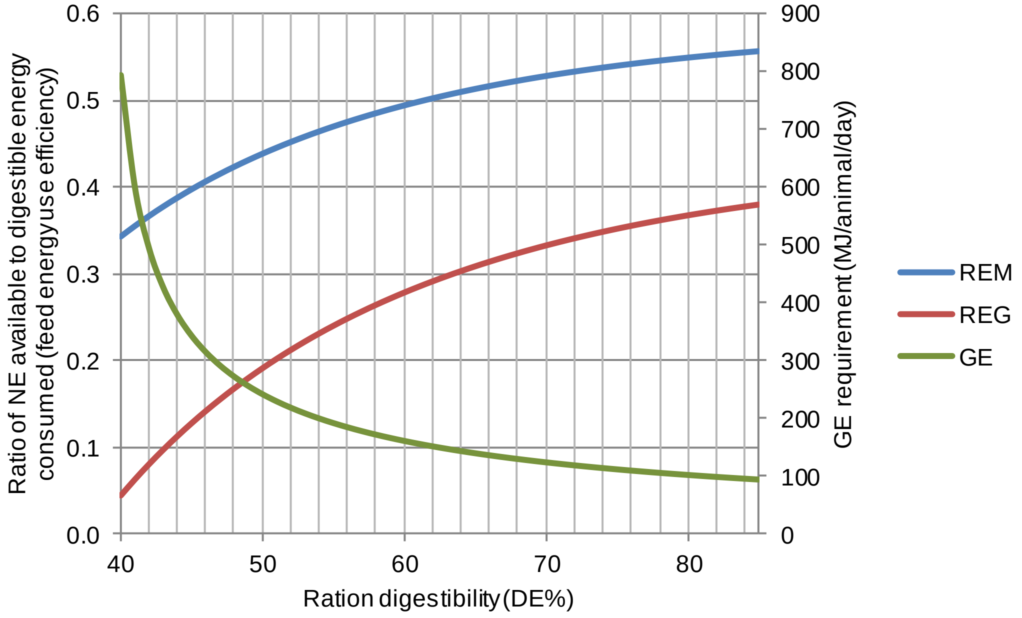

Figure 6.5. The response to increased ration digestibility (DE%) of feed energy use efficiency for maintenance (REM) and growth (REG), and GE requirement. Assumes constant animal net energy (NE) requirements of 30 MJ/day for maintenance and 10 MJ/day for growth. Based on the use of IPCC equations used for the application of nutritional mitigation measures in Chapter five.

Under the proposed methodology presented in Section 6.3. and Section 6.4., additional feed intake (above baseline DMI) is defined by ration digestibility and body weight (through the application of Equation 6.1.). An improvement in ration digestibility increases feed intake and with a known energy density of feed the additional GE available to the animal is calculated. These relationships are not linear; instead the equations create an increasing rate of return (Figure 6.6.). An increase in ration digestibility from a lower baseline (e.g. DE% from 40% to 50%) will see less of an increase in feed intake than an increase from a higher baseline (e.g. DE% from 50% to 60%).

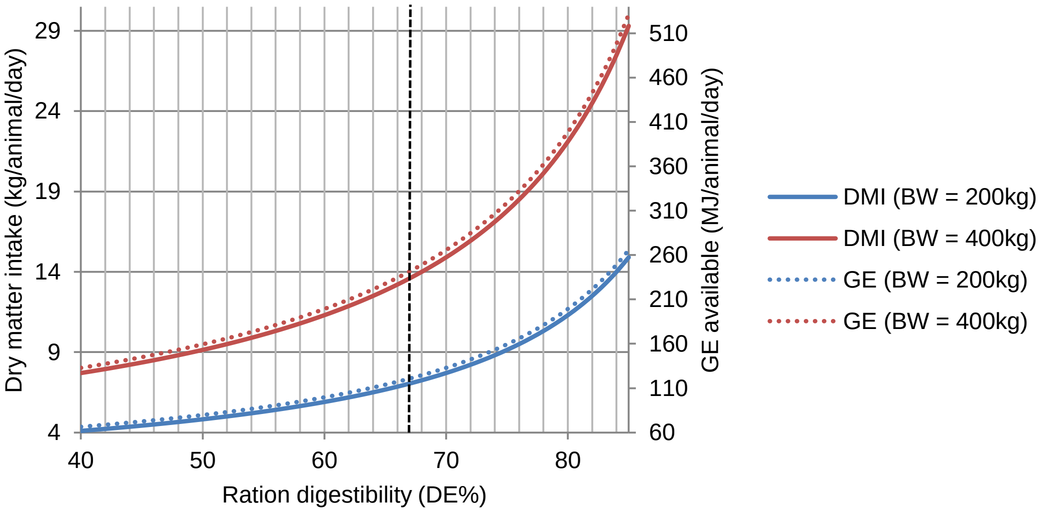

Figure 6.6. The response to increased ration digestibility (DE% = digestible energy as a percentage of gross energy) of dry matter intake and the resulting gross energy (GE) available to animals. Assuming constant animal body weights of 200kg and 400kg; and feed energy density of 18.45 MJ/kg. The dashed line indicates the maximum ration digestibility obtained through the application of nutritional mitigation measures in this study. Based on the application of IPCC equations for a novel approach for the application of nutritional mitigation measures discussed in Chapter six.

The response of productivity parameters to a 1% increase in the digestibility (DE%) of baseline feed ration are presented for breed groups IZ and IZ x BT in Table 6.3.. The maximum increase in ration digestibility with the packages of mitigation measures in this study is 6.6%. Confidence in these results is improved as they are to similar magnitudes as those used by previous studies (Table 6.1.). The performance responses are variable between systems with different baseline scenario parameters. Increase in feed intake (Equation 6.1.) and increase in growth rates (Equation 6.9.) are dependent on baseline body weights. Whilst increase in milk yield and adult body weight are dependent on both the intake increase, and on how additional energy is allocated (either to lactation or body reserves (Section 6.3.4.).

Table 6.3. Productivity parameter response to an example mitigation measure of 1% increase in ration digestibility (DE%). Total additional production caused by the improvement to the feed rations is shown, with the percentage change from baseline scenarios in brackets. See Section 2.2. for herd type definitions.

Proposed response to DE% change	**IZ** **+**		**IZ x BT** **+++**	
Baseline ration DE%	55.1		59.4	
Improved ration DE%	56.1		60.4	
AF additional intake (kg day)	0.2	(2.3%)	0.3	(2.5%)
AF additional GE (MJ/day)	3.1	(2.3%)	4.9	(2.5%)
AF additional BW (kg)	2.4	(0.8%)	2.5	(0.6%)
AF additional milk yield (kg/year)	0.0	(0.0%)	59.7	(2.3%)
AM additional BW (kg)	2.6	(0.7%)	3.7	(0.7%)
Reduction in AFC (years)	-0.25	(-5.8%)	-0.17	(-4.9%)

DE% = digestible energy as a proportion of gross energy; AF = adult female, GE = gross energy available, BW = body weight; AM = adult male; AFC = age at first calving (also representative of age at maturity for males)

In reality, feed intake is influenced by a range of factors beyond ration digestibility, the extent and diversity of which is illustrated in Figure 6.7.. Instead of the curves of increasing rates of return shown in Figure 6.6., intake increase would likely follow a diminishing rate of return to a certain level; defined in the short term by a range of satiety signals (Forbes, 1996) and in the long term by reaching a mature body state maintenance equilibrium (Speakman and Krol, 2005; Speakman *et al.*, 2002).

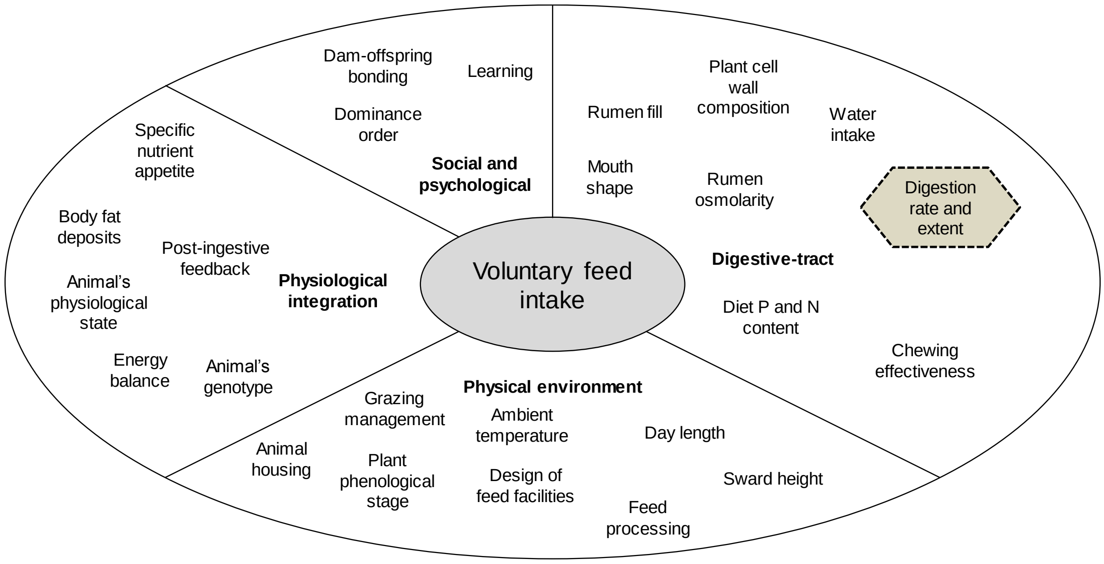

Figure 6.7. Illustration of the multiple functions which influence animal feed intake, of which the method proposed here only considers digestion rate. Adapted from Dryden (2008).

For instance, feedlot cattle displayed variation in feed intake when the ratio of roughage to concentrate was altered in their feed ration. Intake increased as roughage content was reduced and concentrate increased, but only to a point, beyond which further increases in concentrate caused a decline in feed intake (Costa *et al.*, 2005) (Figure 6.8.).

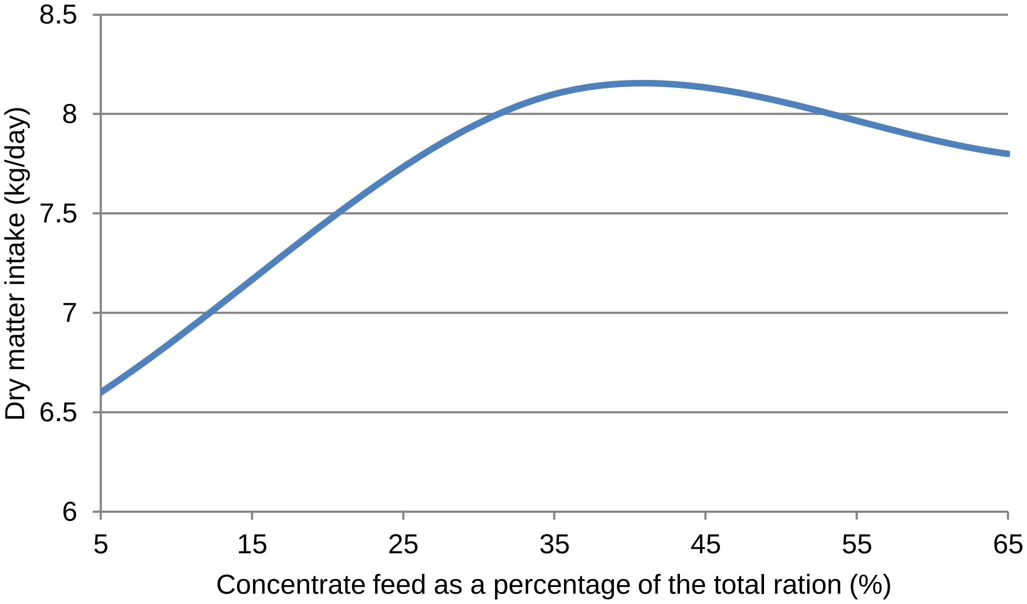

Figure 6.8. An experimental response of feed intake to the increasing ratio of concentrate to roughage (assumed increasing ration digestibility) in the ration of beef feedlot cattle. From Costa *et al.* (2005).

When roughages are a high proportion of the ration, the key limiting factor to intake is likely to be the volume of digesta (digesting feed) in the reticulo-rumen (rumen fill). As ration digestibility increases, this limiting factor will be reduced, as digesta will pass through the rumen at a higher rate. When concentrates are increased to an excessive proportion of the ration, the limiting factor becomes neuro-hormonal, this limiting factor is lacking in the methodology presented here. However, as the animals in this study are understood to be nutritionally limited and often under-nourished, an assumption is made that when rations are improved they are on the positive gradient of the curve and therefore intake will increase fairly rapidly (Dryden, 2008). The maximum ration digestibility (of 67%) obtained through the application of packages of mitigation measures to baseline rations is illustrated in Figure 6.6.. Therefore, the proposed methodology is applied with confidence to the study systems; for more general application (in particular for animals close to their maximum productivity potential) this would need further investigation.

6.6. Sensitivity analysis

The methodology proposed here is a novel approach to addressing an acknowledged limitation when using the Tier 2 methodology to assess feed related mitigation measures. However, there is considerable uncertainty as to how animals will respond to additional energy made available to them (discussed in Section 6.5.), and uncertainty surrounding the use of the Tier 2 equations to predict animal performance. Feed related mitigation measures increase ration digestibility and are likely to improve animal production performance, therefore they influence Ei. The proposed methodology estimates this improvement to animal production performance. A sensitivity analysis was conducted to see the influence on the magnitude of a change in Ei, if each of the steps in Figure 6.9. has a weaker or stronger response than that predicted.

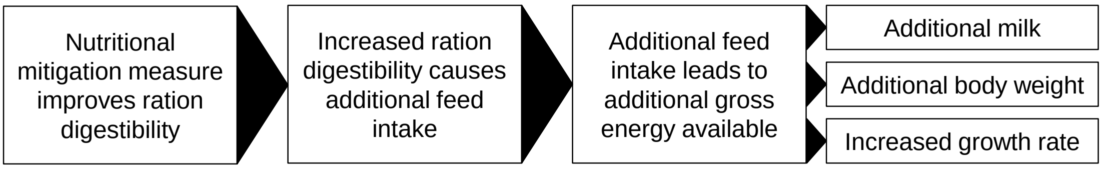

Figure 6.9. Conceptual diagram showing the model estimation of the change to animal productivity when a nutritional mitigation measure improves the ration digestibility. Whether gross energy is allocated to additional milk, additional body weight or increased growth rate is dependent on animal cohort and breed type, as discussed in Section 6.3.4..

Each response in the proposed model (each step in Figure 6.9.) was altered in isolation by +10% and -10%; for instance additional feed intake, predicted by Equation 6.1., is increased by +10% and -10%. The impacts on the change to Ei result are summarised in Figure 6.10. and Figure 6.11..

As expected (See Table 5.3.) variation in the increase to ration DE% has substantial influence on the magnitude of a change to Ei. As additional intake and additional GE are both dependent on ration DE%, variation in these responses also has substantial influence on the magnitude of a change to Ei. Considering Figure 6.10. if the additional feed intake response is 10% greater than predicted, the Ei will be reduced by 4% more than predicted. The influence of variation in additional milk yield from additional GE on Ei is dependent on herd breed type; the more additional energy allocated to lactation, the more the variation in lactation response will influence Ei. A unit of additional energy allows proportionally less additional adult body weight, than additional lactation; therefore variation in additional body weight response has little effect on the magnitude of change to Ei. All additional energy for young stock of all breed types is allocated to increasing growth rates; therefore variation in this response has impact on change in Ei for all herd types.

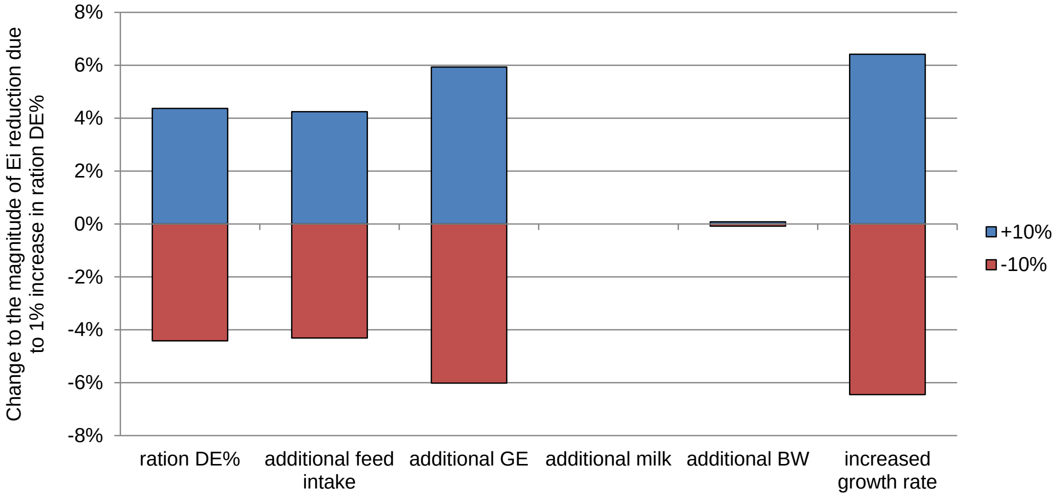

Figure 6.10. The influence on the magnitude of emissions intensity (Ei) change caused by a mitigation measure that increase ration DE% by 1%, if each predicted response is greater or weaker than that predicted. Results shown for applying a hypothetical mitigation measure, increasing ration digestibility (DE%) by 1%, to a herd of IZ + type.

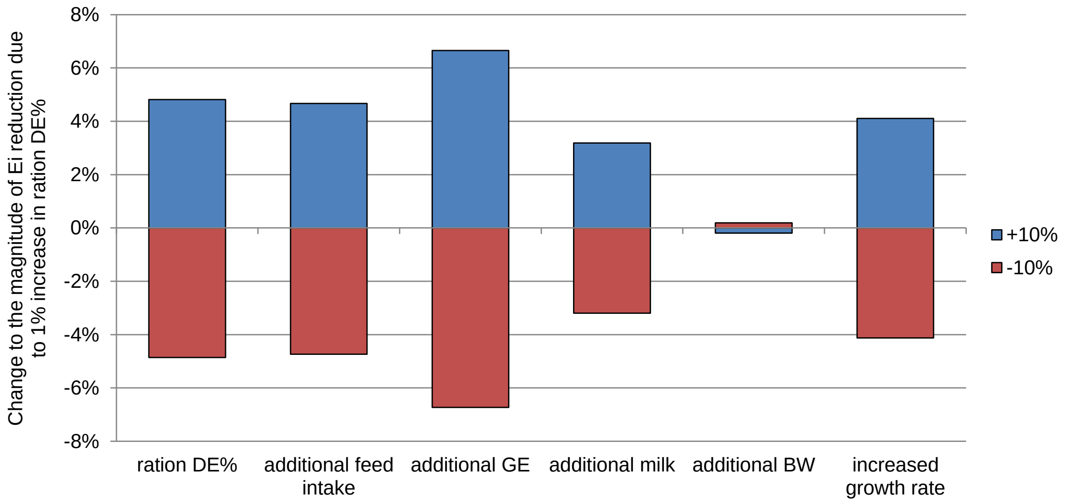

Figure 6.11. The influence on the magnitude of emissions intensity (Ei) change caused by a mitigation measure that increase ration DE% by 1%, if each predicted response is greater or weaker than that predicted. Results shown for applying a hypothetical mitigation measure, increasing ration digestibility (DE%) by 1%, to a herd of IZ x BT +++ type.

The results of this sensitivity analysis suggest that if this method was to be improved further, research should first explore the change in total ration when feed related mitigation measures are applied, to discern how in reality an animal will respond (e.g. feed intake changes). Secondly, the animal response to additional energy available, in terms of additional growth rate and additional milk yield, should be investigated to see if the productivity changes seen in Table 6.3. are realistic, and to what extent of feed ration improvement they hold true.

6.7. Important caveats to the proposed methodology

As discussed, this methodology is novel and can only be considered a preliminary step in a models ability to predict the response of animal performance to improved feed rations. Therefore, as well as the consideration of the sensitivity analysis results, other issues are recognised and summarised below.

Diminishing returns

Figure 6.6. suggests an increasing rate of animal performance improvement to increments of increased feed ration digestibility. As suggested by experimental studies (Costa *et al.*, 2005), animal productivity improvements may increase rapidly as rations are first improved, however, the response is likely to slow as other factors limit the animal (Figure 6.7.). It is assumed that the study systems are nutritionally limited, so feed ration improvements will see an increase in animal productivity. However, caution is advised if the method is used to predict further feed ration improvements or improvements to systems already at a high level of productivity.

Energy allocation

This methodology relies on assumptions and simplification being made as to which physiological processes the additional energy will be allocated to; this is a likely source of inaccuracy. For example, when assuming energy is allocated to an ability to maintain a greater body weight (as in Zebu adult females and both Zebu and Taurine adult males), for simplicity the energy required for the growth to reach this weight is not considered. In reality the increased body weight from additional available energy is likely to be less than predicted under this model, at least initially as a portion of additional energy would be used for growth. In addition, when assuming additional energy is allocated to increase growth rates (as for both replacement females and replacement males) it is not considered, that with an increased growth rate, maintenance energy requirements (a function of body weight) would also increase. Therefore, growth from additional units of energy would be limited by energy required to maintain the additional body weight gained. There are also other productivity improvements which could be expected when nutrition is improved; a refinement of this methodology could include increased fertility rates, reduced abortion and mortality rates, and increased offtake rates of animals slaughtered for meat. Under the present model no additional energy is allocated to increased activity, increased pregnancy or increased labour.

Other key assumptions, which could in reality limit feed intake and the application of this methodology, include:

a) An assumption that increased feed intake can be maintained through sustained access and affordability of feed resources for study livestock keepers,
b) An assumption that net annual energy balance is around zero. The calculations in this method are based on annual average of milk yield and body weight, ignoring the likely seasonal variation in energy availability (Sawadogo *et al.*, 1999) and the energy dynamics involved in body tissue catabolism (CSIRO, 2007).

Evidently, this proposed methodology is a significant simplification of complex biological processes. A logical next step in the development of such a methodology would be to investigate the response of cattle production parameters to improved feed rations under study farm conditions. However, the objective here was to improve the analysis of mitigation measures through the modelling of their application to baseline systems. This objective was met and the proposed methodology applied to GLEAM V1.0; the effects on results are discussed in the following section.

6.8. Influence on modelled mitigation measures

As in Chapter five, mitigation measures were preliminarily applied to baseline systems in isolation, and then as packages considering the interactions between mitigation measures. However, in this round of modelling the methodology to estimate animal productivity changes when feed related mitigation measures are applied to production systems was included (Figure 6.4.). The influence this has on the abatement potential and cost-effectiveness of abatement is summarised for typical herds of type IZ+ and IZ x BT+++ in Table 6.4. and Table 6.5., respectively.

Table 6.4. The influence on annual abatement potential (AP = tCO_2eq/herd/year) and cost-effectiveness (CE = $\$/tCO_2eq$) of abatement for mitigation measures (MM), with the addition of feed related animal productivity improvement, when applied to a typical herd of type IZ +. Numbers in brackets are the percentage difference in AP and CE between when the proposed method is not applied (-) and when the proposed method is applied (+). The change to annual cost-saving (win-win) AP as a percentage of total emissions, and the annual financial benefit from cost-saving measures are also included.

MM	**AP -**	**AP +**		**MM**	**CE -**	**CE +**	
FMD	1.9	1.9	(0.0%)	FMD	-79.0	-79.0	(0.0%)
LSD	1.8	1.8	(0.0%)	LSD	-92.0	-92.0	(0.0%)
Hay	0.2	0.1	(-74.0%)	Hay	-18.0	-75.3	(319.2%)
Tryps	1.3	1.6	(21.5%)	Tryps	-11.7	-11.1	(-5.5%)
Urea	0.9	1.1	(12.8%)	Urea treatment	38.9	19.1	(50.9%)
GNC +5%	1.8	2.6	(38.9%)	GNC +5%	245.9	169.8	(30.9%)
win-win AP	*11.7%*	*12.0%*	*(2.2%)*	*win-win AP financial benefit ($)*	*340.7*	*343.2*	*(0.8%)*

PC measures not included on this table as addition of proposed methodologies changed the form in which PC was applied (i.e. +5%, 30%, 40%, see section), therefore direct comparison of the effect of the model change would not be appropriate.

Table 6.5. The influence on annual abatement potential (AP = tCO$_2$eq/herd/year) and cost-effectiveness (CE = \$/tCO$_2$eq) of abatement with the addition of the methodology proposed to estimate changes to animal productivity when nutritional mitigation measures are applied to a typical herd of type IZ x BT +++. Numbers in brackets are the percentage difference in AP and CE between when the proposed method is not applied (-) and when the proposed method is applied (+). The change to annual cost-saving (win-win) AP as a percentage of total emissions, and the annual financial benefit from cost-saving measures are also included.

MM	**AP -**	**AP +**		**MM**	**CE -**	**CE +**	
FMD	1.5	1.5	(0.0%)	FMD	-408.7	-408.7	(0.0%)
LSD	1.7	1.7	(0.0%)	LSD	-412.7	-412.7	(0.0%)
Tryps	1.2	1.2	(0.0%)	Tryps	-130.1	-130.1	(0.0%)
Urea	0.3	0.6	(86.0%)	Urea treatment	-57.4	-166.1	(189.5%)
Hay	1.6	2.0	(28.8%)	Hay	-70.1	-82.4	(17.6%)
GNC +5%	2.0	3.3	(69.9%)	GNC +5%	212.5	-6.6	(103.1%)
win-win AP	*10.3%*	*17.0%*	*(64.2%)*	*win-win AP financial benefit (\$)*	*1617.1*	*1773.2*	*(9.7%)*

PC measures not included on this table as addition of proposed methodologies changed the form in which PC was applied (i.e. +5%, 30%, 40%, see section), therefore direct comparison of the effect of the model change would not be appropriate.

As expected, the additional methodology to estimate animal productivity changes in response to the application of nutritional mitigation measures does not have an impact on the abatement potential and cost-effectiveness of abatement for animal health mitigation measures (FMD, LSD and Tryps). An exception is when the Tryps measure is applied following the application of the hay improvement nutritional measure, as the Tryps measure uses the altered hay improvement scenario as a baseline to consider abatement potential and cost-effectiveness.

In general, the inclusion of feed related animal productivity improvement results in an increase in the abatement potential, and cost-effectiveness of abatement, for feed related mitigation measures. The proposed methodology suggests that when feed related measures are applied and feed rations improve, herds will produce more protein (through improved milk yields, greater body weights and increased growth rates). This increase in productivity is greater than any increases in GHG emissions (which will occur as intake of feed is higher) and as such the Ei decreases. The increased protein production also increases herd revenues and the cost-effectiveness of applying measures that improve the feed ration. An exception to this rule is the hay improvement mitigation measure applied to the IZ+ herd (Table 6.4.). In this instance, the emissions associated with the increase in feed intake of the overall ration increase more than animal productivity and as such the reduction in Ei is reduced. In contrast, with the inclusion of animal productivity improvements when groundnut cake is increased in the ration for herd type IZ x BT +++, the increase in productivity is greater than the increase in emissions and has enough influence on reducing the Ei and increasing revenues to change this mitigation measure from being costly to be cost-saving. It is evident that the balance between changes in productivity and changes in emissions is important to the abatement potential and cost-effectiveness results.

Despite the uncertainties with this proposed method, the overall impact of its inclusion is evident. The assumptions made suggest that considering animal productivity improvement is particularly important when considering mitigation measures for herd types thought to be nutritionally limited and expected to be able to produce more protein should these limitations be removed. For instance the proportion of total annual GHG emissions that could be abated through win-win measures increases by 64%, and financial savings increase by 10%, when animal productivity improvement is considered for IZ x BT +++ herds. As demonstrated by the sensitivity analysis, to further substantiate the estimations of productivity improvement future research should look to quantify animal responses to improved nutrition, in particular changes to intake and the partitioning of additional energy to different physiological purposes.

CHAPTER SEVEN

CHANGING HERD TYPES

7.1 Emissions abatement by changing breed types and management levels

Modelling in Chapter five and Chapter six suggested there is potential to abate GHG emissions from study herds by improving productivity through nutritional and animal health mitigation measures. Previous commentators have also suggested improved breeding as an intervention to reduce emissions (Gerber *et al.*, 2013b). As the study herds with different breed types and management levels have different Ei, it may be possible to reduce emissions by changing to herd types with lower Ei. Table 7.1. shows the GHG Ei, annual protein production, and benefit to cost ration (annual revenue against costs) for each herd type; based on this, IZ x BT +++ is assumed optimal, and other herd types will be changed to this type. Herd changes from IZ x BT ++ to IZ x BT+++ are not considered, as the improvements required would be based on management rather than breeding; which is covered in the mitigation measures applied to systems in Chapter five and Chapter six. BT ++++ herds are also not considered as a change to IZ x BT +++ is likely to increase emissions.

Table 7.1. Emissions intensities (Ei), annual protein yields and benefit-to-cost ratios for typical herds of each herd type. See Section 2.2. for herd type definitions.

Herd performance	**IZ**	**IZ**	**IZ x GZ**	**IZ x GZ**	**IZ x BT**	**IZ x BT**	**BT**
	+	**++**	**+**	**++**	**++**	**+++**	**++++**
GHG Ei (kg CO_2eq/kg protein)	340	192	310	167	191	113	108
Protein (kg/herd/year)	132	254	129	289	230	543	532
Benefit to cost ratio[1]	1.22:1	1.32:1	1.23:1	1.44:1	1.58:1	1.75:1	1.47:1

[1] Benefit to cost ratios (annual per cow revenue against costs) calculated by Marshall et al. (2016b) for the study herds

7.2 Modelling a change between herd types

It is proposed that for relevant herds a gradual change to the 'optimal' type (IZ x BT +++) could be achieved over ten years (Table 7.2.). AI programmes to improve breeds have occurred previously in Senegal (Seck and Fadiga, 2016); therefore AI will be used to direct the herd breed change. The increased cost of using AI (as opposed to the use of free access bulls in baseline scenarios) is included the cost of making in the herd change, and includes repeated AI attempts before successful pregnancies. The proportion of the herd composed of baseline or improved animals (and their respective management) changes based on:

a) the fertility rate of cows,
b) the mortality rate of each cohort in the herd, and
c) the time taken for improved calves to reach maturity

For each year these parameters are a weighted average of the changing proportion of baseline and improved animal types. Likewise, annual net income is calculated based on the costs and revenues weighted by the changing proportion of baseline and improved animal types. Herd costs relate to the whole herd, whilst revenues are largely based on productive adults (Marshall *et al.*, 2016b); therefore costs are based on the composition of the whole herd, whilst revenues are based on the composition of the adult portion of the herd.

As demonstrated in Table 7.2., the costs of improving the herd type increase ahead of revenues. Therefore, in those years where costs are greater than revenues and net income (profit) negative (years 2, 3, 4 and 5 in Table 7.2.), loans are used to reach zero net income. It is assumed households can still function as they largely have another source of income (Section 2.4.2.). Loans typically have an annual interest rate of 14% and a two year grace period before a two year payback period starts (this is based on answers in the SDG questionnaires from study farmers who have used loans previously).

Table 7.2. Proposed timeline to change herd type from baseline to improved, demonstrated for IZ+ to IZ x BT+++.

Herd parameters	**Year of project to change herd type**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Adult females baseline herd type	100%	100%	100%	100%	88%	64%	40%	16%	2%	0%
Adult females improved herd type	0%	0%	0%	0%	12%	36%	60%	84%	98%	100%
Herd revenue ($)	4,276	4,276	4,276	4,276	5,490	7,918	10,346	12,775	14,169	14,350
All animals baseline herd type	100%	87%	74%	62%	44%	32%	20%	8%	1%	0%
All animals improved herd type	0%	13%	26%	38%	56%	68%	80%	92%	99%	100%
Herd costs ($)	3,898	4,523	5,127	5,712	6,569	7,138	7,714	8,284	8,605	8,646
Profit ($ = herd revenue – herd costs)	377	-248	-851	-1,436	-1,079	780	2,633	4,490	5,564	5,704
Loan required ($)	0	248	851	1,436	1,079	0	0	0	0	0
Business as usual(BAU)/baseline profit ($)	771	771	771	771	771	771	771	771	771	771
Benefit from herd change ($ = profit – BAU profit)	0	0	0	0	0	9	1,862	3,719	4,793	4,932
Cost of herd change ($ = profit lost + cost of loans)	394	0	0	151	668	1,389	1,527	655	0	0
Herd Ei (kg CO_2eq/kg protein)	340	340	340	340	313	258	203	148	117	113
Abatement potential (tonnes CO_2eq)	0	0	0	0	4	11	18	25	30	30

The annual Ei of protein production is a weighted average based on the changing proportion of baseline and improved adults in the herd. Total annual abatement potential is calculated by assuming the baseline quantity of protein is produced every year, but with decreasing Ei. We assume increasing efficiency of protein production, and for the purpose of calculating Ei assume production levels to remain constant. The net present value (NPV) of changing herd type is calculated over a time period as the sum of discounted benefits (additional revenue, above the business as usual baseline, due to changing herd type) minus the sum of the discounted costs (any revenue lost, compared to the business as usual baseline, and loan costs, due to the changing herd type). The time period for calculating NPV should consider the economic decisions of current livestock keepers and have relevance for the next generation; therefore benefits and costs are discounted over both 10 and 30 years. Other studies considering livestock projects in SSA have suggested using a discount rate of 10% (Shaw *et al.*, 2013).

7.3 Cost-effectiveness of emissions abatement by changing herd types

Table 7.3. shows the abatement potential and cost-effectiveness of abatement through changing an individual herd breed type and management level, from a baseline to an improved scenario. Modelling suggests that improving a herd breed type and management level is a cost-effective intervention to abate emissions through improved productivity. Variation in annual abatement potential illustrated in Table 7.3., is due to differences between respective baseline scenarios and improved scenario Ei. The greater the difference in Ei, the greater the improvement to the efficiency of protein production and the greater the annual abatement potential. The largest increase in net income (profit) is seen for those livestock keepers currently rearing low productivity cattle. The shift to the improved scenario represents the greatest increase in productivity and revenue for them.

Table 7.3. The annual abatement potential (AP; tCO_2eq/year), cost-effectiveness (CE; \$/tCO_2eq), and average annual financial benefit (\$; \$/year) of changing the breed type and management level from baseline to improved scenarios for individual typical herds. CE is presented using a net present value (NPV) calculated over 10 and 30 years, with both 5% and 10% discount rates. Figures in brackets represent abatement potential as a percentage of total herd emissions.

Baseline scenario	**IZ +**			**IZ ++**			**IZ x GZ +**			**IZ x GZ ++**		
Improved scenario	**IZ x BT +++**			**IZ x BT +++**			**IZ x BT +++**			**IZ x BT +++**		
	AP	**CE**	**$**	**AP**	**CE**	**$**	**AP**	**CE**	**$**	**AP**	**CE**	**$**
NPV over 10 years												
10% discount rate	15 (33%)	-42	617	10 (21%)	-40	413	12 (29%)	-48	555	8 (17%)	-32	252
NPV over 30 years												
10% discount rate	25 (55%)	-30	745	17 (34%)	-34	563	21 (52%)	-35	718	13 (27%)	-34	447

7.4 Barriers to changing herd types

The modelled timeline of gradual change of herd type, from baseline scenarios to an improved scenario, is a highly simplified example of one way breeding interventions could improve productivity and reduce emissions. The assumptions used suggest that GHG emissions could be reduced cost-effectively, by changing the herd type to increase productivity. Other studies have previously demonstrated that improved breeding and crossbreeding can improve the incomes of practicing households (Kahi and Nitter, 2004; Roschinsky *et al.*, 2015). However, as there still remains uncertainty concerning breed-change interventions (Marshall, 2014), and the adoption of such practices remains limited in SSA (Abdulai and Huffman, 2005), it is important to discuss the potential limitations to such breed and management changes in reality.

The breeding decisions of livestock keepers in developing regions are commonly based on a variety of factors beyond production. These include: the local feed resources available, likely disease burdens and the provision of ancillary benefits (e.g. insurance and financing) (Bebe *et al.*, 2003). Therefore, there could be both cultural and environmental barriers to livestock keepers choosing to use improved breeds (Ejlertsen *et al.*, 2013). In addition, the complexity and level of understanding required for successful crossbreeding has been suggested as a limitation in some scenarios (Ejlertsen *et al.*, 2013; Roschinsky *et al.*, 2015). The FGDs in Chapter three suggested that within the study households there is an incentive to improve animals and that knowledge of how to do this (including the use of improved breeds) was good. However, this could be an artefact of households' involvement with the SDG project, so limits the scalability of this assumed motivation.

There is an understanding that the lower productivity indigenous Zebu breeds are commonly more adapted to the local, often challenging, environments (Berman, 2011). It could be argued that a change from 'low-input, low-output' to 'high-input, high-output' systems is accompanied by a loss in resilience, which is likely to become more important as regions experience the impacts of climate change

(Hoffmann, 2010). This is likely to limit the uptake of such intervention by low-input livestock keepers, who are commonly risk averse (Andrieu *et al.*, 2015; Itty *et al.*, 1997; Udo *et al.*, 2016).

For breed-change interventions to be successful the accompanying production environments must also be improved (Chagunda *et al.*, 2015, 2004). In the method used here, it is assumed that management improvements would accompany breed change, and the financial costs of this are included in the assessment. However, it is assumed that the supporting infrastructure, markets and resources, critical for sustainable improvements (Rege *et al.*, 2011; Roschinsky *et al.*, 2015), are also sufficient for improved breed intervention to be successful. For instance, it is assumed that the appropriate AI services needed to crossbreed, and financial loans, are available to the livestock keepers; and that livestock keepers will effectively improve management alongside breed improvement. Based on the FGDs with livestock keepers in Chapter three, and evidence of previous interventions in the region (e.g. AI programmes), these are likely to be valid assumptions for the study livestock keepers. However, such intervention applied by the wider population of livestock keepers cannot be implied with as high a level of confidence.

7.5 Trade-offs when choosing an optimal herd type

This thesis was part of the wider SDG project, which made an assessment of the most appropriate cattle breed type for Senegalese livestock keepers (Marshall *et al.*, 2016b). In this assessment a range of factors were considered, including livestock keeper breed preference, milk yields, cost: benefit, and GHG Ei; these are summarised in Table 7.4.. The project demonstrated the complexity involved in a decision concerning the most appropriate breed type, but extolled the crossbred type IZ x BT, as being the most appropriate production system. The aspects favouring the IZ x BT breed type can largely be linked to a higher level of animal productivity. In contrast, when food safety and gender impacts are considered, the traditional indigenous Zebu with lower management input appear more appropriate.

In many of the commonly used feed materials (groundnut cake, brans and compound feeds) aflatoxin (toxic by-products from mould growth) levels were found to be above World Health Organization recommended limits (Marshall *et al.*, 2016a). Aflatoxins are associated with both impacts on livestock production and human health risks (including liver cancer, infant stunting and immune system suppression) (Grace *et al.*, 2015); the levels observed were high enough to cause concern (Marshall *et al.*, 2016a). The traditional indigenous Zebu herds, with a lower level of management input rely much less on supplementary feeds and more on grazing pasture; therefore the aflatoxin risk is lower (Marshall *et al.*, 2016a).

There is also suggestion that if herds shift to more productive breeds with a higher level of management, potentially increasing market orientation and male involvement, women lose much of the control of milk sales and income (Marshall *et al.*, 2017). This could be disadvantageous for household welfare as a whole, as indications often show women spend more on education and food (Herrero *et al.*, 2013a).

This thesis contributed to the wider assessment by calculating the GHG Ei, a common issue linked to cattle production (Chapter one). However, currently no other environmental aspects are considered. For instance, the impacts of the different cattle systems on water and land degradation should be considered, as both are points of concern for Senegal (Djaman *et al.*, 2017; Miehe *et al.*, 2010).

Table 7.4. Summary of broader factors considered as part of the SDG project. Bold text indicates the suggested best option, with regards to the factor considered. Table adapted from Marshall *et al.* (2017). See Section 2.2. for herd type definitions.

Herd factors considered	**IZ**	**IZ**	**IZ x GZ**	**IZ x GZ**	**IZ x BT**	**IZ x BT**	**BT**
	+	**++**	**+**	**++**	**++**	**+++**	**++++**
Livestock keeper preference (male/female)[1]	✓/✓	✓/✓	✓/✓	✓/✓	**✓✓✓/✓✓✓**	**✓✓✓/✓✓✓**	✓✓/✓
Milk productivity (litres milk/cow/annum)	175	568	223	640	508	**1315**	**1422**
Cost: benefit ($/annum/cow)[2]	96	227	105	299	378	**767**	**652**
Environmental sustainability (GHG Ei kgCO_2eq/kg protein)	340	192	310	167	191	**113**	**110**
Food quality (milk protein/fat)	Milk protein - no significant difference between herd types Milk fat - herd type variation, but trends changed with cow parity						
Food safety (aflatoxins)[3]	**✳✳✳✳**	✳✳✳	**✳✳✳✳**	✳✳✳	✳✳✳	✳✳	✳
Gendered impacts	**Women control income from milk sales in the majority of households**				Women control income from milk sales in fewer households		

[1] Greater number of ✓ indicates greater frequency of preference amongst livestock keepers
[2] Cost: benefit: profit per cow = revenue per cow – costs per cow
[3] Greater number of ✳ indicates better food safety (i.e. less occurrence of aflatoxins in cattle feeds)

7.6 Conclusions regarding changing herd type

As part of this project it was important to consider productivity improvement and emissions abatement through breeding interventions, especially as breed changes are increasingly debated for developing regions (Marshall, 2014). Modelling based on emissions and household profits suggests that it would be cost-effective to change the herds with low productivity to match the herds with higher productivity, and that over an extended time period the benefits to the livestock keeper outweigh the costs. However, as discussed, it is important to consider how appropriate such an intervention would be for specific circumstances, particularly with regards to uncertain impacts of climate change, potential losses of resilience, and other household level impacts.

CHAPTER EIGHT

CONCLUSIONS

8.1. Summary of contribution and main findings

The significant contribution of livestock rearing to anthropogenic GHG emissions is widely understood (Gerber *et al.*, 2013b; Steinfeld *et al.*, 2006); despite this the demand for livestock produce is predicted to increase significantly, particularly within developing regions (Alexandratos and Bruinsma, 2012). Therefore, to minimise associated increases in GHG emissions, research should focus on developing our understanding of methods to increase the efficiency of livestock production in regions such as SSA. This thesis contributes towards this by analysing ways of improving productivity in Senegalese cattle systems.

Limited data sets are a commonly referenced constraint of past GHG emissions modelling studies (Opio *et al.*, 2013). However, the use of a case study, through the well-established SDG project (Box 1.2.), enabled modelling to be based on comparably accurate and focused data. In addition, past modelling projects have been highly criticised for being ‘top-down’ and highly *ex situ*; not recognising ‘social behaviours’ and ‘cultural positions’ of those within modelled systems (Chambers, 1983; Crane, 2010). The direct links with case study households allowed valuable livestock keeper engagement, greatly improving the projects relevance (Keating *et al.*, 2010).

The key findings of the thesis are:

A. **Most study livestock keepers aspire to improve the productivity of their herds**. The benefit of rearing a smaller number of higher producing animals is widely recognised. Other functions of cattle (e.g. savings and ceremonial or social value) and risk aversion were the key reasons given by a minority of livestock keepers not wishing to have smaller herds. FGDs suggested that for productivity improvements to be realised, certain barriers will require consideration:
    - Consistently, livestock keepers cited a lack of financial means to make improvements to their herds. They were unable to afford cattle housing, private AI and improved breeds, or adequate health management and feed.
    - As well as resources being unaffordable, limited access to improved breeds, adequate pasture, labour and veterinarians were commonly referenced.
    - Livestock keepers valued knowledge highly and suggested there was further need for information and training concerning productivity improvement options. Topics of interest included: animal health, milk preservation, and forage treatments and conservation.

B. **There is substantial variation in the Ei of protein production from the different case study production systems.** Current varying levels of productivity, in particular milk offtake (ranging from 323 to 2197 kg/cow/year) and cow fertility rate (ranging from 55% to 71%); combined with variation in feed ration digestibility (ranging from 55% to 63%), cause Ei to range from 110 to 340 kgCO_2eq/kg protein. Substantial differences in Ei between herds with the same breed types demonstrate a real potential for mitigation through improved management of the current systems.

C. **There are options to improve the productivity of the case study systems.** The apparent variation in productivity between current herd systems suggests a theoretical potential to improve productivity. This is reinforced by evidence gathered via consultation with experts, fieldwork undertaken for this thesis and the SDG survey results. The most promising options target cattle nutrition and health.

D. **Significant emissions abatement could be achieved through 'win-win' (cost-saving) interventions.** Results suggest that assuming a constant level of production, GHG emissions could be reduced by between 10% and 12% through interventions that are also cost-saving for livestock keepers. Total annual savings of these interventions range from $340 to $1600 per herd, with the greater savings being for herds with higher productivity breed types (herd annual profits increase by between 30% and 50%).

E. **The effects of changing feeding on animal performance should be included when calculating the change in emissions and cost-effectiveness.** The proposed method for including animal performance response to improved nutrition in the Tier 2 approach demonstrates the influence this has on intervention cost-effectiveness. 'Win-win' emissions abatement potential increased by up to 64%, whilst total annual financial savings increased by up to 10%. The highest increases in abatement potential and savings were seen in the herds with higher productivity breed types. Due to high uncertainty, animal performance responses deserve clarification through future research.

F. **Improving herd breed types and management levels could have significant potential for cost-saving emissions abatement.** Over a proposed ten year period, improving the breed type and management levels of low producing herds could abate between 17% and 55% of herd emissions (assuming a constant production level), whilst incurring annual financial benefits of up to $1582 per herd (increasing annual herd profits by up to 100%). The greatest abatement potential and financial benefits were seen for the current herd types with the lowest productivity. However, certain caveats must be highlighted. Breeding and management decisions by livestock keepers in SSA are commonly based on a variety of factors beyond productivity, and will often involve trade-offs (for instance cattle productivity versus environmental resilience). The supporting infrastructure, markets and resources must also be capable of sustaining these herd changes.

8.2. Research implications

8.2.1. Livestock keepers and policy makers

The results presented in this thesis suggest that there are options for livestock keepers to improve the productivity of their cattle, thereby increasing their profits, whilst increasing food availability and providing the wider social benefit of reduced GHG emissions. The livestock keepers within this study have aspirations to achieve this productivity increase and are largely aware of the mechanisms to do so. However, in order to realise productivity improvements it is likely that livestock keepers will require intervention to improve access to appropriate resources and markets.

The apparent interest amongst study livestock keepers to improve the productivity of their systems could be an artefact of their longer term involvement with the SDG project. Therefore, such changes for the wider livestock keeper population cannot be assumed, and would need further consideration; particularly in the context of risk and resilience. An assessment for Senegalese agriculture highlighted a variety of risks relevant to the livestock sector. These included: extreme droughts, pests, bush fires, disease, crop and livestock product price volatility, land tenure and access, and the uncertainty as to the future impact of climate change (D’Alessandro *et al.*, 2015). A shift from traditional pastoral systems (generally with low productivity, low market orientation and a high level of mobility) to agro-pastoral or semi-intensified systems (with higher productivity through using improved breed types, higher market orientation and a low level of mobility) is likely to reduce the ability of systems to manage such risks and limit their resilience.

There is evidence that the Senegalese Government are committed to improving domestic livestock productivity; for instance the launch of a National Program for Livestock Development in 2005, and several Government implemented AI programmes (Seck and Fadiga, 2016). However, for productivity to be realised interventions must not be proposed in isolation; it is evident, from the substantial variation in productivity and Ei of systems with the same breed types (Figure 5.2.) and from the trade-offs in decision making discussed, effective packages of measures should be designed and promoted. Identification of the most appropriate breed type and its promotion and access, must be accompanied by access to required animal health measures and nutritional resources.

Following the Paris Climate Conference (COP21), and an increased awareness of the role developing countries, such as Senegal, will play in climate change mitigation (République du Sénégal, 2015), this thesis gives indication of the contribution Senegal's livestock rearing population could make. Results suggest cost-saving options, including both animal health and nutritional interventions, exist and could play a key role in livestock keeper engagement. Policy action that facilitates access to productivity improving resources should be accompanied by effective extension services, communicating the knowledge and information to improve utilisation of such resources. A first step could be the support of high performing SDG study herds as demonstrations to promote the existence of the cost-saving options and engage the wider population.

8.2.2. Future research

As discussed in Chapter six, predicting how animal performance will respond to supposed productivity improving interventions, be that through improved animal health (for this study based on literature examples) or improved animal nutrition, introduces a high level of uncertainty. It is also demonstrated how important these productivity responses are when attempting to quantify emissions abatement potential and cost-effectiveness (more crucial for livestock keeper engagement). Therefore, this aspect highly deserves further research efforts. Engagement with *in situ* experimental herds to test the application of productivity improving interventions and accurately record animal performance responses would be the logical next step. Due to the high complexity of such biological processes, production responses will never be constant, but such experiments would significantly improve modelling efforts.

Projects largely based on modelling, such as that demonstrated by this thesis, can provide an important first step in identifying mitigation strategies for livestock systems in developing nations. However, if they are to play a role in effective sustainable development efforts, they need to be part of a broader process in which social, economic and environmental aspects are considered *in situ*.

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APPENDIX A

SENEGAL STUDY SYSTEM FEED RATIONS

Estimation of Senegal study baseline rations

The Senegal Dairy Genetics (SDG) project (Box 1.2.) conducted 14 survey cycles for 220 livestock keeping households, between May 2013 and April 2015. At each survey cycle livestock keepers were asked an extensive range of questions about the management of their cattle since the previous survey cycle. This included questions concerning the feeding of cattle. Standardised rations were estimated for each herd type (Section 2.2.) for both the wet season and the dry season (Table S1); then an annual weighted average ration was used for modelling the systems in GLEAM (Table 2.3.).

Ration proportions were estimated from hourly grazing records, assuming an intake based on animal body weights (daily dry matter intake (DMI) ‘should be in the order of 2% to 3% of the body weight of the mature or growing animals’ (IPCC, 2006)), and additional feeding records (e.g. brans, crop stovers and purchased compound feeds). Due to the high variation in additional feed materials reported by livestock keepers, ‘major feed types’ were identified based on those that made up 90% of the total weight of all feed materials referenced, any further feed materials were grouped under ‘other’ and the weight of this portion divided *pro rata* to the ‘major feed types’. It is assumed that all animals within a herd receive rations of the same composition.

Table S1 Feed ration components (%) for the seven defined production systems, for the wet season and dry season. The components of purchased compound feed are included within the main ration components, then the purchased compound feed proportion of the total ration (% of total ration) is shown in the last row. Derived from information gathered as part of the SDG surveys (2013- 2015). See Section 2.2. for herd type definitions.

Herd type	**IZ**		**IZ**		**IZ x GZ**		**IZ x GZ**		**IZ x BT**		**IZ x BT**		**BT**	
	+	**+**	**++**	**++**	**+**	**+**	**++**	**++**	**++**	**++**	**+++**	**+++**	**++++**	**++++**
Season	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
Maize grain	0.7	0.7	2.3	2.0	1.4	2.2	1.2	2.3	2.8	2.1	2.7	3.9	15.7	9.4
Millet stover	1.5	14.3	3.6	13.0	7.6	13.3	3.4	14.3	2.9	9.4	0.8	4.1	11.2	16.6
Brans	4.6	5.3	11.9	11.1	7.2	9.3	5.9	7.9	12.2	8.3	13.2	14.5	24.3	26.9
Groundnut cake	4.3	5.3	4.4	8.6	4.4	5.9	3.2	7.4	9.1	11.1	8.5	15.3	15.0	18.5
Groundnut shells	0.4	0.4	1.1	1.0	0.9	0.8	0.7	1.0	1.3	0.9	1.9	1.8	3.01	3.9
Natural pasture (grazed)	84.6	68.8	64.8	51.1	69.3	58.8	76.1	57.2	57.4	48.6	47.4	27.6	14.4	4.5
Natural pasture (cut and carry)	1.5	0.8	4.7	3.0	2.4	0.5	3.8	0.4	6.1	1.6	13.0	2.1	4.8	1.5
Natural pasture (hay)	2.3	4.5	7.1	10.3	6.6	9.2	5.8	9.5	8.1	17.9	12.5	30.5	11.6	18.7
Purchased compound feed	3.7	3.6	10.0	8.7	8.4	7.4	6.5	8.9	11.4	7.7	16.8	16.3	26.8	34.6

APPENDIX B

SENEGAL STUDY SYSTEM MODELLING PARAMETERS

Table S2 Animal productivity model input parameters, assumptions and source information defining the baseline systems. See Section 2.2. for herd type information.

Herd type		**IZ**		**IZ x GZ**		**IZ x BT**		**BT**	**Source**[1]
		+	**++**	**+**	**++**	**++**	**+++**	**++++**	
Animal body weights									
Adult female weight	kg	294	317	302	309	333	414	433	SDG
Calf weight at birth	kg	21	22	21	22	23	29	30	SDG
Milk									
Milk offtake	kg/year/lactating cow	323	877	411	989	937	2032	2197	SDG
Milk suckled	kg/year/lactating cow	516	516	464	464	511	511	489	SDG
Milk fat content	% by mass	4.9	4.9	5.1	5.1	5.1	5.1	5.8	Ema *et al.* (2014)
Milk protein content	% by mass	3.7	3.7	3.7	3.7	3.5	3.5	3.7	Ema *et al.* (2014)
Reproduction									
Age at first calving	years	4.3	3.8	3.7	3.7	3.5	3.5	3.3	SDG
Fertility rate adult females	proportion giving birth/year	0.57	0.63	0.55	0.71	0.55	0.71	0.63	SDG
Mortality									
Death rate at birth	proportion dying at birth/1st week	0.04	0.04	0.14	0.14	0.04	0.04	0.08	SDG
Death rate female calves (0-1)	proportion dying aged 0-1	0.02	0.02	0.02	0.02	0.03	0.03	0.07	SDG
Death rate male calves (0-1)	proportion dying aged 0-1	0.04	0.04	0.04	0.04	0.04	0.04	0.04	SDG
Death rate young animals (1-2)	proportion dying aged 1-2	0.03	0.03	0.03	0.03	0.04	0.04	0.06	SDG
Death rate young animals (2-3)	proportion dying aged 2-3	0.03	0.03	0.03	0.03	0.04	0.04	0.06	SDG
Death rate adult females	proportion dying/year	0.02	0.02	0.02	0.02	0.03	0.03	0.07	SDG
Death rate adult males (AFC - death)	proportion dying/year	0.04	0.04	0.04	0.04	0.04	0.04	0.04	SDG

[1] SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI)

Table S2 continued Animal productivity model input parameters, assumptions and source information defining the baseline systems. See Section 2.2. for herd type information.

Herd type		IZ		IZ x GZ		IZ x BT		BT	Source[1]
		+	++	+	++	++	+++	++++	
Offtake									
Offtake young males age 0-1	proportion sold /year	0.1	0.1	0.1	0.1	0.1	0.1	0.1	SDG
Offtake young males age 1-2	proportion sold /year	0.2	0.2	0.2	0.2	0.2	0.2	0.2	SDG
Offtake young males age 2-3	proportion sold /year	0.3	0.3	0.3	0.3	0.3	0.3	0.3	SDG
Offtake young females age 0-1	proportion sold /year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	SDG
Offtake young females age 1-2	proportion sold /year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	SDG
Offtake young females age 2-3	proportion sold /year	0.2	0.4	0.2	0.3	0.3	0.4	0.3	SDG
Offtake adult females	proportion sold /year	0.2	0.2	0.2	0.2	0.2	0.2	0.1	SDG
Offtake adult males	proportion sold /year	0.3	0.3	0.3	0.3	0.3	0.3	0.3	SDG
Other herd information									
Adult female replacement rate	proportion of cows replaced/year	0.2	0.2	0.2	0.2	0.2	0.2	0.2	SDG
Bull to cow ratio		0.3	0.3	0.2	0.3	0.3	0.3	0.3	SDG
Labour	average hours of draft work/year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	SDG

[1] SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI)

Table S3 Fertiliser application rates model input parameters, assumptions and source information defining the baseline systems. See Section 2.2. for herd type information.

Herd type		IZ		IZ x GZ		IZ x BT		BT	Source
		+	++	+	++	++	+++	++++	
Synthetic fertiliser application									
Maize grain	kgN/ha/year	53.9	53.9	53.9	53.9	53.9	53.9	53.9	Brazil import[1]; Richetti and Ceccon (2014) and FAO (2004)
Millet stover	kgN/ha/year	7.9	7.9	7.9	7.9	7.9	7.9	7.9	Sonneveld *et al.* (2016) and IFDC (2014)
Bran	kgN/ha/year	17.8	17.8	17.8	17.8	17.8	17.8	17.8	Sonneveld *et al.* (2016) and IFDC (2014)
Groundnut cake	kgN/ha/year	5.5	5.5	5.5	5.5	5.5	5.5	5.5	Sonneveld *et al.* (2016) and IFDC (2014)
Groundnut shells	kgN/ha/year	5.5	5.5	5.5	5.5	5.5	5.5	5.5	Sonneveld *et al.* (2016) and IFDC (2014)
Senegal pasture	kgN/ha/year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Assumed zero
Pasture (cut and carry)	kgN/ha/year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Assumed zero
Senegal hay	kgN/ha/year	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Assumed zero
Manure fertiliser application									
Maize grain	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time cattle confined
Millet stover	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Bran	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Groundnut cake	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Groundnut shells	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Senegal pasture	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Pasture (cut and carry)	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined
Senegal hay	kgN/ha/year	1.3	1.3	1.3	1.3	0.4	0.4	0.1	Assumed, based on time spent confined

[1] Personal communication with Dr Cheikh Alioune Konate, Nutritionist for NMA Sanders feed merchants, Dakar. 6 May 2016; (Konate CA, 2016, personal communication)

Table S4 Feed material transport and harvest yield assumptions and source information, defining the baseline systems. See Section 2.2. for herd type information.

Herd type		IZ		IZ x GZ		IZ x BT		BT	Source
		+	**++**	**+**	**++**	**++**	**+++**	**++++**	
Transport by land									
Maize grain	km	1364	1364	1364	1364	1364	1364	1364	Brazil import[1]
Bran	km	722	722	722	722	722	722	722	Guinea & St. Louis import[1]
Millet stover, groundnut cake and shells, pasture (cut and carry), Senegal hay	km	0	0	0	0	0	0	0	Local[1]
Transport by water									
Maize grain	km	6708	6708	6708	6708	6708	6708	6708	Brazil import[1]
Millet stover, bran, groundnut cake and shells, pasture (cut and carry), Senegal hay	km	0	0	0	0	0	0	0	Local[1]
Ration materials gross yields harvested									
Maize grain	kgDM/ha/year	1119	1119	1119	1119	1119	1119	1119	Brazil FAO STAT
Millet stover	kgDM/ha/year	624	624	624	624	624	624	624	Senegal FAO STAT
Bran	kgDM/ha/year	1151	1151	1151	1151	1151	1151	1151	Senegal FAO STAT
Groundnut	kgDM/ha/year	766	766	766	766	766	766	766	Senegal FAO STAT
Senegal pasture	kgDM/ha/year	498	498	498	498	498	498	498	Sawadogo *et al.* (1999)

[1] Personal communication with Dr Cheikh Alioune Konate, Nutritionist for NMA Sanders feed merchants, Dakar. 6 May 2016; (Konate CA, 2016, personal communication)

Table S5 Feed material digestibility and nitrogen content assumptions and source information, defining the baseline systems. See Section 2.2. for herd type information.

Herd type		**IZ**		**IZ x GZ**		**IZ x BT**		**BT**	**Source**
		+	**++**	**+**	**++**	**++**	**+++**	**++++**	
Ration materials digestible energy									
Maize grain	DE%	90	90	90	90	90	90	90	Feedipedia[1]
Millet stover	DE%	33	33	33	33	33	33	33	Jarrige *et al.* (1989)
Bran	DE%	73	73	73	73	73	73	73	Feedipedia[1]
Groundnut cake	DE%	85	85	85	85	85	85	85	Feedipedia[1]
Groundnut shells	DE%	16	16	16	16	16	16	16	Jarrige *et al.* (1989) & Feedipedia[1]
Senegal pasture	DE%	55	55	55	55	55	55	55	Jarrige *et al.* (1989)
Pasture (cut and carry)	DE%	55	55	55	55	55	55	55	Jarrige *et al.* (1989)
Senegal hay	DE%	44	44	44	44	44	44	44	Jarrige *et al.* (1989)
Ration materials nitrogen content									
Maize grain	gN/kgDM	15	15	15	15	15	15	15	Feedipedia[1]
Millet stover	gN/kgDM	10	10	10	10	10	10	10	Jarrige *et al.* (1989)
Bran	gN/kgDM	18	18	18	18	18	18	18	Feedipedia[1]
Groundnut cake	gN/kgDM	78	78	78	78	78	78	78	Feedipedia[1]
Groundnut shells	gN/kgDM	10	10	10	10	10	10	10	Jarrige *et al.* (1989) & Feedipedia[1]
Senegal pasture	gN/kgDM	15	15	15	15	15	15	15	Jarrige *et al.* (1989)
Pasture (cut and carry)	gN/kgDM	15	15	15	15	15	15	15	Jarrige *et al.* (1989)
Senegal hay	gN/kgDM	15	15	15	15	15	15	15	Jarrige *et al.* (1989)

DE% = Digestible energy as a proportion of gross energy

[1] www.feedipedia.org

APPENDIX C

FOCUS GROUP DISCUSSION TEMPLATE

Presented below is the Focus Group Discussion template as used by the facilitators. Enumerators and facilitators played key roles in formulating these from English drafts (based on their understanding of what livestock keepers would understand and relate to, as well as the study information requirements). The English translation is provided in italics.

1. Augmentation de production et revenues

(Increase in production and revenues)

1.1. Thème: L'augmentation de production laitière

(Theme: Increase in milk production)

Quelle importance accordée vous a une augmentation de votre production laitière?

(How important is it to increase your milk production?)

a. Très important – j'aimerais augmenter la productivité laitière de mes animaux

   (Very important - I would like to increase the milk productivity of my animals)

b. Peu important – je serais intéressé par une augmentation de ma production laitière

   (Quite important - I would be interested in increasing my milk production)

c. Pas important – je ne suis pas intéressé* *(Not important - I'm not interested*)*

d. Aucune idée *(No opinion)*

Que peut-on faire pour à améliorer la production laitière de vos animaux?

(What can be done to improve the milk production of your animals?)

Quelles sont les obstacles vous empêchant de pratiquer ces précédentes actions?

(What obstacles prevent you from practicing these previous actions?)

*Pourquoi ne voulez-vous pas améliorer votre production laitière?

(Why do you not want to improve your milk production?)

1.2. Thème: L'augmentation de revenues à la vente des animaux

(Theme: Increase in animal sales)

Quelle est l'importance pour vous d'augmenter vos revenues à la vente des animaux?

(How important is it for you to increase your income from the sale of animals?)

a. Très important – j'aimerais augmenter mes revenues à la vente des animaux *(Very important - I would like to increase my income on the sale of animals)*
b. Peu important – je serais intéressé par une augmentation de mes revenues à la vente des animaux *(Quite important - I would be interested in an increase in my income from the sale of the animals)*
c. Pas important – je ne suis pas intéressé* *(Not important - I'm not interested*)*
d. Aucune idée *(No opinion)*

Que peut-on faire pour améliorer les revenues à la vente des animaux?

(What can be done to improve the returns from the sale of animals?)

Quelles sont les obstacles vous empêchant de pratiquer ces précédentes actions?

(What obstacles prevent you from practicing these previous actions?)

*****Pourquoi vous ne voulez pas améliorer vos revenues à la vente ?

(Why do you not want to improve your animal sales revenue?)

2. Mesures spécifiques pour une augmentation de production

(Specific measures for an increase in production)

2.1. Rationnement *(Feeding)*

Souhaiteriez-vous améliorer le rationnement des aliments concentres de vos animaux que d'habitude?

(Would you like to improve the feeding of animals using more concentrated feed?)

a. *Oui *(Yes)*
b. **Non *(No)*
c. Aucune idée *(No opinion)*

*Si oui, pourquoi vous ne le faites pas? (*If yes, why do you not do it?)*

**Si non, pourquoi? (*If no, why?)*

Souhaiteriez-vous améliorer les pâturages (utilisation et culture) de vos animaux?

(Would you like to improve the pasture (use and cultivation) for your animals?)

a. *Oui *(Yes)*
b. **Non *(No)*
c. Aucune idée *(No opinion)*

*Si oui, pourquoi vous ne le faites pas? (*If yes, why do you not do it?)*

**Si non, pourquoi? (*If no, why?)*

Souhaiteriez-vous améliorer la gestion de fourrage conservée (forme d'ensilage ou en bottes de foin, etc…)?

(Would you like to improve the management of preserved fodder (e.g. silage or hay, etc ...)?)

a. *Oui *(Yes)*
b. **Non *(No)*
c. Aucune idée *(No opinion)*

*Si oui, pourquoi vous ne le faites pas? (*If yes, why do you not do it?)*

**Si non, pourquoi? (*If no, why?)*

Voudriez-vous améliorer l'ingestion des fourrages (un traitement de la paille ou un hachage de l'herbe)?

(Would you like to improve the digestibility of forages (e.g. treatment of straw or grass)?)

a. *Oui *(Yes)*
b. **Non *(No)*
c. Aucune idée *(No opinion)*

*Si oui, pourquoi vous ne le faites pas? (*If yes, why do you not do it?)*

**Si non, pourquoi? (*If no, why?)*

2.2. Sante animale *(Animal health)*

Quelle est l’importance de l’amélioration de la santé des animaux pour augmenter la productivité de l’élevage?

(How important is improving animal health to increase livestock productivity?)

a. Très important – j’aimerais augmenter la sante de mes animaux
   (Very important - I would like to increase the health of my animals)
b. Peu important – je serais intéressé par une amélioration de la sante de mes animaux
   (Quite important - I would be interested in improving the health of my animals)
c. Pas important – je ne suis pas intéressé par sante de mes animaux
   (Not important - I am not interested in health of my animals)
d. Aucune idée *(No opinion)*

Quelles sont les maladies les plus fréquemment rencontrées dans vos élevages bovins?

(Which diseases are most frequently encountered on your cattle farms?)

Les trois maladies les plus néfastes sur la production des animaux?

(Name the three most harmful diseases for the production of animals?)

2.3. Amélioration génétique *(Genetic improvement)*

Quelles sont les caractéristiques de vos animaux que vous voudriez changer?

(What are the characteristics of your animals that you would like to change?)

Comment y procéder? *(How could you proceed?)*

Qu’est-ce que vous empêche de le faire? *(What prevents you from doing so?)*

2.4. Autre gestion *(Other management)*

Cela vous intéressé-t-il de faire la même production avec moins d'animaux?

(Are you interested in producing the same volumes with fewer animals?)

Si oui, pourquoi? (*If yes, why?)*

Si non, pourquoi? (*If no, why?)*

Y a-t-il une relation entre la récolte et la production des animaux?

(Is there a relationship between crop harvesting and the production of animals?)

Oui: No de personnes *(Yes: number of people)*

Si oui, pourquoi? (*If yes, why?)*

*Non : No de personnes *(No: number of people)*

Si non, pourquoi? (*If no, why?)*

Quelle importance accordez-vous à cette relation?

(How important is this relationship to you?)

a. Très important – j'aimerais augmenter mes récoltes
   (Very important - I would like to increase my crops)
b. Peu important – je serais intéressé par une amélioration de mes récoltes
   (*Quite important - I would be interested in improving my crops)*
c. Pas important – je ne suis pas intéressé par mes récoltes
   (Not important – I'm not interested in crops)
d. Aucune idée *(No opinion)*

Comment les éleveurs pensent améliorer leur production agricole?

(As breeders, how could you improve agricultural production?)

Qu'est-ce que vous empêche de le faire? *(What prevents you from doing so?)*

3. Question de fin *(Final question)*

Avons-nous omit une idée importante pouvant contribuer à l’amélioration de la production de l’élevage?
(Have we missed any important ideas that can contribute to the improvement of livestock production?)

Merci beaucoup à toutes et à tous pour votre disponibilité et vos informations utiles
(Thank you very much to all of you for your availability and useful information)

APPENDIX D

SENEGAL STUDY SYSTEM MONETARY ASSUMPTIONS

Table S6 Revenue and cost assumptions used in economic assessments of herds. See Section 2.2. for herd type information. All values are in US Dollars ($), converted from Central African Franc (CFA) using exchange rate 1CFA = $0.0016

Herd type		**IZ**		**IZ x GZ**		**IZ x BT**		**BT**	**Source**[1]
		+	**++**	**+**	**++**	**++**	**+++**	**++++**	
Revenue sources									
Milk sale price	per litre	0.8	0.8	0.8	0.8	0.8	0.8	0.8	SDG
Male calf sale price	per animal	257	257	257	257	339	339	1003	SDG
Young male sale price	per animal	282	282	329	329	858	858	1493	SDG
Mature male sale price	per animal	418	418	617	617	694	694	1280	SDG
Young female sale price	per animal	402	402	420	420	882	882	1760	SDG
Adult female sale price	per animal	346	346	402	402	1000	1000	1000	SDG
Baseline health costs									
Female calf health-care cost	per animal, per year	0.19	0.39	0.32	0.46	0.71	0.73	0.92	SDG
Male calf health-care cost	per animal, per year	0.09	0.18	0.15	0.21	0.33	0.34	0.43	SDG
Young male health-care cost	per animal, per year	0.08	0.17	0.14	0.20	0.31	0.32	0.40	SDG
Young female health-care cost	per animal, per year	0.17	0.34	0.28	0.40	0.63	0.65	0.81	SDG
Mature male health-care cost	per animal, per year	0.04	0.09	0.07	0.11	0.16	0.17	0.21	SDG
Cow health-care cost	per animal, per year	0.34	0.68	0.55	0.80	1.24	1.28	1.60	SDG
Additional health costs									
FMD Vaccine	per dose	0.1	0.1	0.1	0.1	0.1	0.1	0.1	field visits
LSD vaccination	per dose	0.1	0.1	0.1	0.1	0.1	0.1	0.1	field visits
Antibiotic	per treatment	0.8	0.8	0.8	0.8	0.8	0.8	0.8	field visits

[1] SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI); field visits = carried out by author (May 2016)

Table S6 continued Revenue and cost assumptions used in economic assessments of herds. See Section 2.2. for herd type information. All values are in US Dollars ($), converted from Central African Franc (CFA) using exchange rate 1CFA = $0.0016

Herd type		**IZ**		**IZ x GZ**		**IZ x BT**		**BT**	**Source**[1]
		+	**++**	**+**	**++**	**++**	**+++**	**++++**	
Baseline feed costs									
Male calf	per animal, per year	20	53	31	57	58	105	198	SDG
Young male	per animal, per year	55	144	86	158	158	280	529	SDG
Mature male	per animal, per year	89	221	130	238	233	414	758	SDG
Female calf	per animal, per year	14	39	23	42	43	78	147	SDG
Female young	per animal, per year	40	105	62	114	114	203	383	SDG
Cows	per animal, per year	40	105	62	114	114	204	385	SDG
Additional feed costs									
Groundnut cake	per kg as purchased	0.30	0.30	0.30	0.30	0.30	0.30	0.30	SDG /field visits
Brans	per kg as purchased	0.12	0.12	0.12	0.12	0.12	0.12	0.12	SDG / field visits
Purchased compound feed	per kg as purchased	0.38	0.38	0.38	0.38	0.38	0.38	0.38	SDG / field visits
Hay	per kg as purchased	0.02	0.02	0.02	0.02	0.02	0.02	0.02	SDG / field visits
Other costs									
Labour cost	per herd, per year	560	560	560	560	560	560	560	SDG
Watering costs	per herd, per year	35	35	35	35	35	35	35	SDG

[1] SDG = Information collected by, or derived from information collected by, the Senegal Dairy Genetics project (ILRI); field visits = carried out by author (May 2016)

APPENDIX E

GLEAM RESULTS FOR MITIGATION MEASURES APPLIED TO OTHER HERD TYPES

Table S7 GLEAM results for mitigation measures (MM) applied in isolation (assuming no interaction between measures). Abatement potential (AP) (tCO_2e/herd/year) and cost-effectiveness (CE) ($\$/tCO_2e$) of MM are presented in order of CE.

	IZ x GZ +	
MM	**AP**	**CE**
FMD	1.8	-93.6
LSD	2.0	-90.3
Hay	0.4	-20.8
Tryps	1.8	-18.9
Urea	0.8	16.9
Cowpea	5.4	66.4
GNC +5%	2.0	132.6
GNC CP13%	1.8	134.9
PC 30%	1.5	1088.3
PC +5%	0.4	1119.2

	IZ x GZ ++	
MM	**AP**	**CE**
FMD	1.5	-214.3
LSD	1.9	-195.7
Tryps	1.5	-47.9
Hay	0.5	-36.8
Urea	1.0	19.3
Cowpea	6.3	119.6
GNC +5%	2.4	248.9
GNC CP13%	1.9	296.3
PC +5%	0.4	2131.3
PC 30%	1.7	2149.8

	BT ++++	
MM	**AP**	**CE**
FMD	1.6	-315.1
LSD	2.0	-290.5
Urea	1.1	-150.0
Tryps	1.6	-114.9
Hay	1.0	-87.9
GNC +5%	2.2	10.4
GNC CP17%	0.9	33.8
Cowpea	8.2	53.4
PC +10%	0.5	2156.3
PC 40%	0.2	3515.3

FMD: Remove the burden of Foot and Mouth Disease
LSD: Remove the burden of Lumpy Skin Disease
Hay: Improved nutritional value of hay through optimal timing of harvesting
Tryps: Remove the burden on Trypanosomiasis
Urea: Urea treat crop stovers
Cowpea: Replace current forages in baseline rations with cowpea forage
GNC +5%: Increase the groundnut cake proportion of the baseline ration by 5%
GNC 13/15/17CP%: Increase the groundnut cake proportion of the baseline ration until total ration crude protein equals 13/15/17% (dependent on current ration composition, herd productivity and productivity potential)
PC 30/40%: Increase the purchased concentrate (compound) feed proportion of the baseline ration so it composes 30/40% of total ration (dependent on current ration composition, herd productivity and productivity potential)
PC +5/10%: Increase the purchased concentrate (compound) feed proportion of the baseline ration by 5/10% (dependent on current ration composition, herd productivity and productivity potential)

Table S8 GLEAM results for mitigation measures (MM) applied as packages (considering interaction between measures). Abatement potential (AP) (tCO$_2$e/herd/year) and cost-effectiveness (CE) ($/tCO$_2$e) of MM are presented in order of application to the systems (order defined by CE when measures were applied in isolation)

	IZ x GZ	
	+	
MM	**AP**	**CE**
FMD	1.8	-93.6
LSD	1.7	-107.6
Hay	0.4	-26.1
Tryps	1.2	-25.1
Urea	0.9	19.9
GNC +5%	1.6	195.1
PC 30%	0.4	4527.6

	IZ x GZ	
	++	
MM	**AP**	**CE**
FMD	1.5	-214.3
LSD	1.6	-228.8
Tryps	1.1	-63.7
Hay	0.5	-49.4
Urea	1.0	23.1
GNC +5%	2.0	362.3
PC +5%	0.1	9734.2

	BT	
	++++	
MM	**AP**	**CE**
FMD	1.6	-315.1
LSD	1.8	-337.9
Urea	1.3	-151.0
Tryps	1.1	-158.2
Hay	0.9	-113.9
GNC +5%	1.0	147.5
PC +10%	-0.1	

FMD: Remove the burden of Foot and Mouth Disease
LSD: Remove the burden of Lumpy Skin Disease
Hay: Improved nutritional value of hay through optimal timing of harvesting
Tryps: Remove the burden on Trypanosomiasis
Urea: Urea treat crop stovers
GNC +5%: Increase the groundnut cake proportion of the baseline ration by 5%
PC 30/40%: Increase the purchased concentrate (compound) feed proportion of the baseline ration so it composes 30/40% of total ration (dependent on current ration composition, herd productivity and productivity potential)
PC +5/10%: Increase the purchased concentrate (compound) feed proportion of the baseline ration by 5/10% (dependent on current ration composition, herd productivity and productivity potential)

APPENDIX F

Salmon, G.R., Marshall, K., Tebug, S.F., Missohou, A., Robinson, T.P. and MacLeod, M. (2017). The greenhouse gas abatement potential of productivity improving measures applied to cattle systems in a developing region. *Animal.*

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animal

The greenhouse gas abatement potential of productivity improving measures applied to cattle systems in a developing region

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Developing countries are experiencing an increase in total demand for livestock commodities, as populations and per capita demands increase. Increased production is therefore required to meet this demand and maintain food security. Production increases will lead to proportionate increases in greenhouse gas (GHG) emissions unless offset by reductions in the emissions intensity (Ei) (i.e. the amount of GHG emitted per kg of commodity produced) of livestock production. It is therefore important to identify measures that can increase production whilst reducing Ei cost-effectively. This paper seeks to do this for smallholder agro-pastoral cattle systems in Senegal; ranging from low input to semi-intensified, they are representative of a large proportion of the national cattle production. Specifically, it identifies a shortlist of mitigation measures with potential for application to the various herd systems and estimates their GHG emissions abatement potential (using the Global Livestock Environmental Assessment Model) and cost-effectiveness. Limitations and future requirements are identified and discussed. This paper demonstrates that the Ei of meat and milk from livestock systems in a developing region can be reduced through measures that would also benefit food security, many of which are likely to be cost-beneficial. The ability to make such quantification can assist future sustainable development efforts.

Keywords: greenhouse gases, ruminant, productivity, mitigation, Senegal

Implications

This cost-effectiveness (CE) analysis suggests measures that could reduce greenhouse gas (GHG) emissions intensity (Ei) from varying baselines of a selection of Senegalese cattle systems, while improving the productivity and profitability of systems. The implementation of policies could encourage adoption of these measures, which would provide both private and social benefits.

Introduction

Developing countries are experiencing an increase in total demand for livestock commodities, as populations and per capita demands increase. The increased production, required to meet this demand and maintain food security, will lead to proportionate increases in GHG emissions; unless they are offset by reductions in the Ei of livestock production (Gerber *et al.*, 2013). Emissions intensity is a measure of the quantity of GHG emitted per unit of output, for example kg of carbon dioxide equivalent (kgCO_2eq) per kg of milk. Meat and milk produced by cattle in developing countries often have a higher Ei than the same commodities produced in developed countries. A recent study suggested the regional average Ei of milk from sub-Saharan Africa (SSA) is around 9 kgCO_2eq/kg milk, compared with 2 kgCO_2eq /kg milk in North America and Western Europe (Opio *et al.*, 2013). High Ei often reflects low levels of herd productivity, for instance low milk yields, slow growth rates and high mortalities. It is therefore suggested it should be possible to reduce Ei, and increase food availability, by improving herd productivity (Gerber *et al.*, 2013).

Previous studies investigating the GHG Ei of SSA cattle systems are frequently based on Intergovernmental Panel on Climate Change (IPCC) GHG inventory guidelines (Dong *et al.*, 2006). However, such Ei estimations vary considerably; for example Opio *et al.* (2013) estimate Ei for SSA milk at around 270 kgCO_2eq/kg protein, whereas Weiler *et al.* (2014) and Udo *et al.* (2016) estimate for Kenyan milk 50 to 60 kgCO_2eq/kg protein (Ei converted from kgCO_2eq/kg milk to kgCO_2eq/kg protein assuming protein content of milk is 3.3%). It is likely that differences in productivity are responsible for this variation; Opio *et al.* (2013) assume milk

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yields to be <500 kg/cow per year, whereas Weiler *et al.* (2014) and Udo *et al.* (2016) assume more than 1500 kg/cow per year. This variation demonstrates the importance of herd level analysis to improve the accuracy of Ei estimations, from which development opportunities can then be accurately assessed.

Beyond the complexity of GHG emissions allocation to milk and meat, functional allocation of GHG emissions remains a contentious topic. Weiler *et al.* (2014) and Udo *et al.* (2016) demonstrated that Ei decreased by around 20% when changing from allocation of emissions to protein only to allocation to a broader range of cattle functions (e.g. protein, manure, finance, insurance, perceived wealth and dowry). Although it is important to recognise that cattle in SSA have functions beyond protein production, and some non-market products can be economically quantified using opportunity value (Udo *et al.*, 2016); other socio-cultural functions (e.g. symbols of wealth and identity, and use for dowry) remain a challenge to value (Weiler *et al.*, 2014). However, in the context of GHG mitigation, a priority for success is the identification of potential options to improve productivity that both reduce emissions and increase net profits for livestock keepers, who are the key actors in any successful development. This paper presents a herd level assessment of various agro-pastoral cattle systems in Senegal (from low input to semi-intensified), with the specific aims of: (a) defining 'baseline' GHG Ei of produce, (b) identifying a set of mitigation measures with potential for application to these systems, and (c) estimating the GHG emissions abatement potential (AP) and CE of these measures.

Livestock rearing supports more than a third of the population and contributes to around 4.8% of Senegal's gross domestic product (Ministère du Commerce, 2013). It is also recognised as an opportunity for poverty alleviation, deserving of appropriately applied development policies (Roland-Holst and Otte, 2007). The analysis presented here was primarily based on data collected by the International Livestock Research Institute's (ILRI) Senegal Dairy Genetics project (https://senegaldairy.wordpress.com/), from 220 cattle keeping households around the cities of Thiès and Mbacké. Situated in the peanut agro-ecological zone, this region has a semi-arid climate with an average rainfall of 400 mm in a short wet season (July to October). Cattle are reared for milk and meat in largely agro-pastoral systems (Tebug *et al.*, 2015; Marshall *et al.*, 2016).

Material and methods

Households were categorised depending on (a) the dominant breed type kept (Table 1) and (b) the level of management input. Household feed cost was used as a proxy for management input and is indicated by + (the lowest level of management input), ++, +++ and ++++ (the highest level of management input). The methodological steps followed are illustrated in Figure 1 and described in the following sections.

Table 1 *Breed groups into which cattle keeping households were categorised based on the dominant breed in their herds*

Breed group	Description	Number of households
IZ	100% zebu Gobra or zebu Maure; Low productivity, high resilience to local environment	120
IZ × GZ	25% to 50% zebu Guzerat; Guzerat recently introduced from Brazil, with improved meat productivity	40
IZ × BT	25% to 50% Montbeliarde or Holstein/Friesian; taurine breeds bring high milk productivity but low resilience to local environment	46
BT	75% to 100% Montbeliarde or Holstein/Friesian; taurine breeds bring high milk productivity but low resilience to local environment	14

IZ = indigenous zebu; IZ × GZ = indigenous × Guzerat zebu cross; IZ × BT = indigenous zebu × taurine cross; BT = taurine.

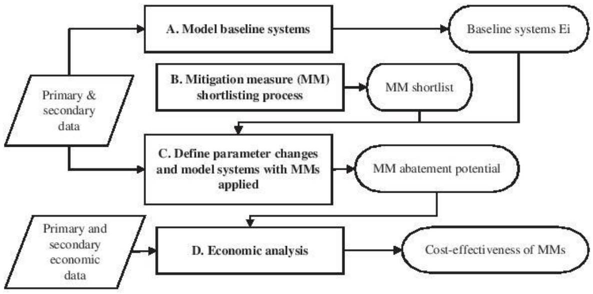

Figure 1 Overview of the methodological stages. Ei = emissions intensity.

A. Model 'baseline' systems to calculate emissions intensity for protein production

The Global Livestock Environmental Assessment Model (GLEAM) was developed by the Food and Agriculture Organization of the United Nations. GLEAM uses a life cycle assessment framework, largely based on IPCC Tier 2 methodology, to estimate GHG emissions, livestock commodity production, and ultimately Ei for production at various spatial scales (Gerber *et al.*, 2013; Opio *et al.*, 2013). An Excel version of GLEAM, which enables herd level analysis, was used to calculate 'baseline' system GHG Ei for meat and milk production. The system boundary is cradle to farm-gate, and the emissions categories included are detailed on page 13 of Opio *et al.* (2013). GLEAM first calculates the energy required to maintain livestock and levels of production (based on model input parameters including milk yields and body weights), followed by the quantity of feed needed to fulfil this requirement. Greenhouse gas emissions associated with the feed, manure and those from enteric fermentation are then allocated to protein (milk and meat) produced. For further detail concerning the Ei calculation, see Supplementary Figure S1. Other functions of cattle in these systems are not included in GHG allocation due to difficulties in accurately quantifying them. Input data used for modelling are detailed in Supplementary Table S1. A sensitivity analysis for the Ei result was carried out by altering each model input parameter, that could be changed when 'baseline' systems are altered to demonstrate the application of mitigation measures, by +10% and −10% (i.e. multiply each parameter by 1.1 and 0.9, respectively). The results of this analysis are summarised in Supplementary Table S2.

B. Mitigation measure shortlisting process

Mitigation measures were shortlisted through three stages (which are further detailed in Supplementary Table S3). The process began with a review of literature to consider options for cattle production systems to improve productivity and reduce Ei. Measures were included in a preliminary shortlist based on options that: (a) avoided high costs, (b) improved system productivity, (c) maintained or reduced absolute emissions and (d) had evidence of feasibility for application in SSA. Inevitably, there was a bias towards shortlisting mitigation measures that could have their application modelled. Secondly, consultation with experts with experience working in animal nutrition, genetics and health management in SSA, removed further measures and saw the addition of others; based largely on measure feasibility and effectiveness. A final stage of shortlisting involved focus group discussions with study livestock keepers (Salmon *et al.*, 2016); this further shortlisted measures based on likelihood of uptake.

The shortlist of mitigation measures is summarised in Table 2. Feed related measures are dominant due to (a) focus group discussions identifying feed interventions as having the greatest immediate feasibility; and (b) the low nutritional value of 'baseline' rations, and evidence of the availability of higher nutritional value feed materials.

C. Defining input parameter changes to model application of shortlisted mitigation measures

'Baseline' systems had model input parameters altered to represent the expected changes to the system when each mitigation measure is applied. Nutritional measures are explained in Table 2 (for nutritional measures the ration compositions are altered, but due to the difficulty in making a prediction of how animals will respond to improved nutrition, production level input parameters (e.g. milk yields) do not change from 'baselines'). Animal health measures are detailed in Table 3; specific changes to production level model input parameters were based on available relevant literature. In the first instance measures were applied standalone, assuming no interaction and comparison made between the single measure applied and the relevant 'baseline' system. Following an assessment of the CE of measures applied standalone, they were then applied as packages in order of CE. To reflect interactions between nutritional measures, the values for groundnut cake (GNC), purchased compound feed (PC), hay and urea treatment were recalculated after the implementation of each measure. For health measures it was assumed that burdens for each disease would be removed from different animals in the herd (i.e. that there were no interactions between these measures). Abatement potential (tonnes of CO_2eq abated/herd per year) was calculated by multiplying the difference in Ei of the system with the measure being considered and without the measure being considered, by the 'baseline' system protein yield.

D. Economic analysis and cost-effectiveness

Economic analysis and CE results were based on a typical herd with eight breeding cows on an annual basis (GLEAM calculates and includes the total herd structure, including young stock and bulls). The CE (\$/tonne of CO_2eq abated) of each mitigation measure was calculated by dividing the cost of implementing the mitigation measure by the change in emissions caused by the application of the measure, using the following equation:

$$\mathrm{CE} = \frac{\text{Gross margin with measure applied} - \text{gross margin without measure applied}}{(\text{Ei with measure} - \text{Ei without measure}) \times \text{baseline protein yield}} \qquad (1)$$

Only private costs of implementation are considered. Individual households do not incur the cost of tsetse removal, to remove the burden of trypanosomiasis (Tryps). It is part of a regional Senegal Government project; however, a relative cost to individual households is included to allow effective comparison with other measures. Social costs (e.g. economic welfare, environmental impacts beyond GHGs, human health and animal welfare) would require further quantification to be included.

Revenue and cost assumptions

Revenue and cost assumptions are detailed in the Supplementary Table S4. The cost of implementing nutritional

Table 2 *Details of shortlisted mitigation measures with potential for application to 'baseline' production systems*

Mitigation measure ID	Description
Nutritional measures	
GNC + 5%	Improved ration supplementation by increasing GNC by 5%; other ration components are reduced in quantity, but remain *pro rata*. This high protein feed resource is locally available as an agro-industrial by-product and present in 'baseline' rations at varying levels
PC 30%/PC 40%/ PC + 5	Improved ration supplementation by increasing PC to be 30% or 40% of the total ration, or increase PC by 5%; depending on the 'baseline' PC proportion of rations. Other ration components are reduced in quantity, but remain *pro rata*. This high energy feed resource will improve the utilisation of poor quality roughages, and is likely to reduce enteric methane and increase animal productivity[1]
Hay	Hay provides a feed resource for when there are shortages. Effective timing of haymaking can maximise protein content and digestibility.[1] 'Baseline' hay is assumed to have DE% of 46.6%.[2] Optimal timing of harvest is assumed to increase DE % to 50%,[2] this includes a loss in quality from storage.[3] The proportions of ration components remain unchanged
Urea treatment	Treating crop stovers in the ration with urea increases their digestibility (baseline DE% = 33.2%,[2] treated DE% = 42.8%[4]) and protein content (baseline gN/kg = 9.6,[2] treated gN/kg = 21.7[4]). The proportions of ration components remain unchanged
Animal health measures	
LSD	Remove LSD burden. LSD is a *capripoxvirus*, with symptoms including skin nodules and fever, which limit cattle productivity. Vaccination is possible.[5]
FMD	Remove FMD burden. FMD is a highly contagious virus, with symptoms including fever and vesicular eruptions on feet and mouth, limiting cattle productivity. Vaccination is possible.[5]
Tryps	Remove Tryps burden. Tryps is a tsetse fly transmitted parasite, causing substantial reduction to cattle productivity.[5] Options for control are available[6]

GNC = groundnut cake; PC = purchased compound feed; DE% = digestible energy as a percentage of gross energy; gN/kg = grams of nitrogen per kg of dry matter; LSD = lumpy skin disease; FMD = foot and mouth disease; Tryps = trypanosomiasis.

[1] See Lukuyu *et al.* (2012).

[2] Based on data in Jarrige (1989).

[3] See Feyissa *et al.* (2014).

[4] See Chenost and Kayouli (1997).

[5] See Blowey and Weaver (2003).

[6] See Bouyer *et al.* (2014).

Table 3 *Percentage changes made to model input parameters to represent the expected productivity changes for a herd when disease burdens are removed*

			Death rate						
			Calves			Young and adult			
Mitigation measure	Milk yield	BW	At birth	Female	Male	1 to 2	2 to 3	3+	Fertility rate
LSD	1.9[1]	1.2[1]	−0.7[1]	−0.7[1]	−0.7[1]	−0.7[1]	−0.6[1]	−0.6[1]	7.1[2]
FMD	1.5[3]	2.1[3]	−0.6[3]	−0.6[3]	−0.6[3]	−0.4[3]	−0.3[3]	−0.3[3]	6.9[2]
Tryps	3.6[4]	0.6[4]	−8.7[4]	−9.4[4]	−7.9[4]	−12.5[4]	−10.0[4]	−14.3[4]	3.0[4]

LSD = remove burden of lumpy skin disease; FMD = remove burden of foot and mouth disease; Tryps = remove burden of trypanosomiasis.

[1] Derived from Daher (1994), Abutarbush *et al.* (2015), Ayelet *et al.* (2013), Hailu *et al.* (2015), Gari *et al.* (2011), Salib and Osman (2011) and assuming prevalence of LSD in the population of 7.1% (Ministère de l'élevage, 2013; Ministère de l'élevage et des productions animales, 2014).

[2] Assumed if an animal had LSD or FMD it would not be fertile, therefore fertility burden equal to respective disease prevalence (Gari *et al.*, 2011; Knight-Jones and Rushton, 2013).

[3] Dervied from Bayissa *et al.* (2011), Lyons *et al.* (2015), Rufael *et al.* (2008), Young *et al.* (2013), Şentürk and Yalçin (2008), Jemberu *et al.* (2014), Onono *et al.* (2013) and assuming prevalence of FMD in the population of 6.9% (Ministère de l'élevage, 2013; Ministère de l'élevage et des productions animales, 2014).

[4] Taken from Shaw *et al.* (2006), and assuming that 50% of Senegal study herds are in regions with the tsetse fly (Bouyer *et al.*, 2014).

mitigation measures represents an annual recurring cost to maintain an improved ration. It was assumed that no additional fixed costs or capital investments are required to improve rations and that any additional costs are included in the price of the feed materials. The cost of implementing measures to remove the burden of foot and mouth disease (FMD) and lumpy skin disease (LSD) also represent an annual recurring cost, with control based on the implementation of effective vaccination. It was assumed that any additional costs are included in the price of the treatment. The costs of Tryps burden removal were based on a project within Senegal to remove the tsetse fly vector (Bouyer *et al.*, 2014). Due to the isolation of the tsetse population in Senegal from the rest of the African tsetse belt, an assumption was made that once the initial project cost of eradicating the tsetse is applied, the eradication will be sustainable without additional costs. Therefore, to consider net present value, the costs and benefits of the tsetse vector eradication were discounted. A discount rate of 10%, suggested by Shaw *et al.* (2013) to be acceptable for livestock projects, was applied over 30 years.

Results

'Baseline' emissions intensity

The Ei for protein (kgCO_2eq/kg protein), with emissions categories defined (enteric, feed related and manure), and protein productivity (defined as kg of protein produced annually per kg of total herd biomass) for 'baseline' systems are illustrated in Figure 2. Key emissions categories are enteric methane (CH_4), feed nitrous oxide (N_2O) (largely from organic nitrogen (N) in urine and manure deposited directly whilst grazing and collected then spread) and carbon dioxide (CO_2) from energy used in the production of GNC and PC. Figure 2 shows a variation in Ei between 'baseline' systems (both between breed groups and between levels of management within breed groups) and the negative trend between herd protein productivity and Ei. The sensitivity analysis (Supplementary Table S2) revealed that the Ei result is most affected by the ration digestibility, milk yield, fertility rate, body weights and age at first calving or maturity; therefore, the 'baseline' values for these parameters are presented in Table 4. Taurine (BT) and zebu taurine cross (IZ × BT) breed groups are fed rations of higher digestibility, largely produce higher milk yields and have greater body weights than indigenous zebu (IZ) and zebu cross (IZ × GZ) breed groups. The level of management is also important in determining milk yield and body weight differences both within and between breed groups. Concerning fertility rate, management appears to be influential, with not an as marked difference between breed groups. Whilst Figure 2 shows the Ei for total protein production, Table 4 shows Ei for both kg of milk and kg of meat. As expected, these follow the same negative trend between herd productivity and Ei.

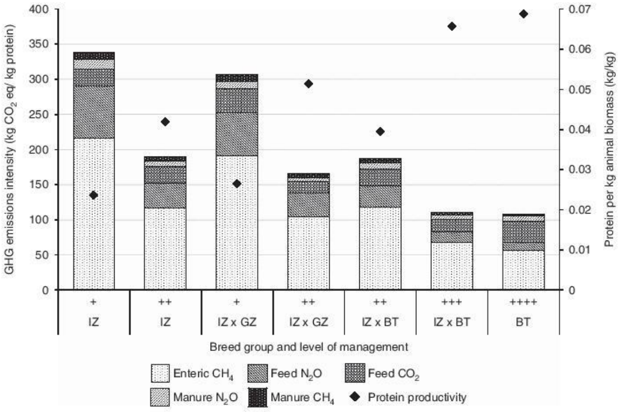

Figure 2 Emissions intensity (kgCO_2eq/kg protein) (bars, left y-axis) and herd protein productivity (annual protein produced per kg of animal biomass in the herd) (diamonds, right y-axis), by breed group and management level. Results shown are for typical herds.

Table 4 *Details of parameters identified by the sensitivity analysis to have most influence on the emissions intensity (Ei) (kgCO_2eq/kg product) result*

Breed group	Management	DE%	Milk yield (kg/cow/year)	BW (kg)	FR (%)	AFC (years)	Ei milk	Ei meat
IZ	+	55.0	323.4	294.4	57.1	4.3	12.9	44.5
	++	56.5	876.9	316.8	63.2	3.8	7.0	25.5
IZ × GZ	+	55.2	411.0	301.7	54.5	3.7	11.5	40.6
	++	55.3	988.8	309.2	70.6	3.7	6.0	22.8
IZ × BT	++	57.2	937.1	333.3	54.5	3.5	6.6	25.3
	+++	58.6	2032.1	413.6	70.6	3.3	3.7	17.0
BT	++++	62.5	2197.8	432.8	63.2	3.3	3.9	15.8

DE% = ration digestibility (expressed as percentage of gross energy); BW = adult cow body weight; FR = adult cow fertility rate; AFC = Age at first calving; Ei milk/meat = (kgCO_2eq/kg product); IZ = indigenous zebu; IZ × GZ = indigenous × Guzerat zebu cross; IZ × BT = indigenous zebu × taurine cross; BT = taurine.

Table 5 *Abatement potential (AP) (tCO$_2$eq/herd/year), percentage reduction to 'baseline' emissions (%) and cost-effectiveness (CE) (\$/tCO$_2$eq) for mitigation measures applied to typical herds*

			Mitigation measure[1]								
Breed group	Management	Result	FMD	LSD	Hay	Tryps	Urea treatment	GNC + 5%	PC 30%	PC + 5%	PC 40%
IZ	+	AP	1.9	1.8	0.2	1.3	0.9	1.8	0.5	–	–
		%	4.3%	4.1%	0.5%	2.9%	2.1%	4.1%	1.1%	–	–
		CE	−79.0	−92.0	−18.0	−11.7	38.9	245.9	5393.4	–	–
	++	AP	1.7	1.7	0.5	1.2	0.9	1.9	0.2	–	–
		%	3.5%	3.6%	1.1%	2.6%	1.8%	3.8%	0.4%	–	–
		CE	−138.5	−155.9	−42.4	−34.4	8.7	255.2	13357.5	–	–
IZ × GZ	+	AP	1.8	1.7	0.4	1.2	0.9	1.6	0.4	–	–
		%	4.5%	4.3%	1.0%	3.1%	2.2%	4.0%	1.0%	–	–
		CE	−93.6	−107.6	−26.1	−25.1	19.9	195.1	4527.6	–	–
	++	AP	1.5	1.6	0.5	1.1	1.0	2.0	–	0.1	–
		%	3.2%	3.4%	1.0%	2.3%	2.1%	4.1%	–	0.2%	–
		CE	−214.3	−228.8	−49.4	−63.7	23.1	362.3	–	9734.2	–
IZ × BT	++	AP	1.5	1.5	0.7	1.0	0.5	1.5	–	–	−0.6
		%	3.4%	3.5%	1.7%	2.4%	1.3%	3.6%	–	–	−1.4%
		CE	−218.1	−231.0	−47.9	−69.7	3.5	254.0	–	–	–
	+++	AP	1.5	1.7	1.6	1.2	0.3	2.0	–	–	−1.4
		%	2.6%	2.9%	2.7%	2.0%	0.5%	3.3%	–	–	−2.3%
		CE	−408.7	−412.7	−70.1	−130.1	−57.4	212.5	–	–	–
BT	++++	AP	1.6	1.8	0.9	1.1	1.3	1.0	–	−0.1	–
		%	2.8%	3.1%	1.5%	2.0%	2.2%	1.7%	–	−0.2%	–
		CE	−315.1	−337.9	−113.9	−158.2	−151.0	147.5	–	–	–

FMD = foot and mouth disease; LSD = lumpy skin disease; Tryps = trypanosomiasis; GNC = groundnut cake; PC = purchased compound feed; IZ = indigenous zebu; IZ × GZ = indigenous × Guzerat zebu cross; IZ × BT = indigenous zebu × taurine cross; BT = taurine.
'–' Represents where measures were not applicable to the respective system or application increased absolute emissions.
[1] See Tables 2 and 3.

Mitigation measure abatement potential and cost-effectiveness
The GHG AP (tonnes of CO$_2$eq abated/herd/year) and CE (\$/tonne of CO$_2$eq abated) of shortlisted mitigation measures applied to typical herds of the 'baseline' systems are detailed in Table 5. Figure 3 is an example marginal abatement cost curve (MACC) for a zebu taurine cross (IZ × BT) herd with a higher level of management. The MACC indicates: (a) the CE of emission abatement (y-axis), (b) the GHG AP for each measure (x-axis) and (c) the total cost of each measure (the area of each bar). Results suggest that across the 'baseline' systems there is potential to abate between 4.7 and 6.7 tCO$_2$eq/herd per year through 'win-win' measures. This represents a respective reduction of between 10% and 13% to annual total herd GHG emissions. Mitigation measures were modelled as packages, applied in order of their CE when initially applied in isolation. As explained in the 'Material and methods' section, efforts were made to avoid double counting of AP.

Discussion

'Baseline' emissions intensity
The Ei results for milk production (4 to 13 kgCO$_2$eq/kg) (Table 4) are similar to those in Opio *et al.* (2013) (9 kgCO$_2$eq/kg for SSA), but greater than those in Weiler *et al.* (2014) and Udo *et al.* (2016) (around 2 kgCO$_2$eq/kg for Kenyan systems). Contrast with Weiler *et al.* (2014) and Udo *et al.* (2016) is likely due to differences in levels of productivity; particularly for the lower producing Senegal systems (300 to 500 kg milk/cow/year), in comparison with Weiler *et al.* (2014) and Udo *et al.* (2016) considering yields from 1500 to over 3000 kg/cow/year. Herd structure is also influential, with productive cows making up 30% to 40% of Senegal study herds, whilst productive cows were 45% to 60% of herds in the studies by Weiler *et al.* (2014) and Udo *et al.* (2016). The higher the proportion of the herd made up of productive animals, the less biomass requiring maintenance (plus the associated emissions) for each unit of produce. The Ei results for meat production (16 to 45 kgCO$_2$eq/kg) (Table 4) are less than Opio *et al.* (2013) (70 kgCO$_2$eq/kg beef). Contrast here is likely due to the Senegal study systems having animals of greater body weight (adult cows weighed between 294 and 433 kg in comparison with 271 kg in Opio *et al.* (2013)), and a higher cow replacement rate (17% to 21% in comparison with 11% in Opio *et al.* (2013)). This results in a greater quantity of meat being produced per animal in the herd. These results demonstrate that for the effective assessment of any development or productivity improvement plans the 'baseline' should be considered in detail.

The variation in Ei results for the 'baseline' systems (Figure 2) demonstrates the potential to reduce GHG

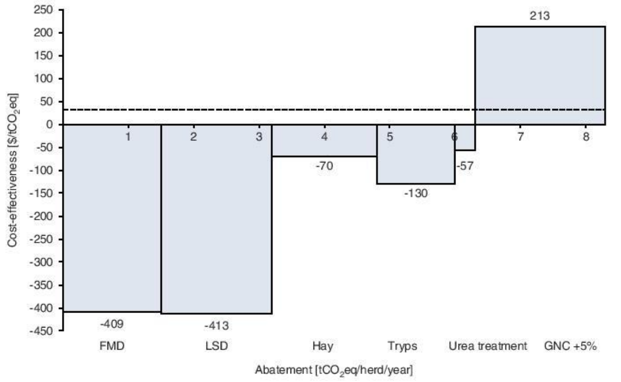

Figure 3 Annual marginal abatement cost curve for a typical herd of zebu taurine crossbreed with a higher level of management. Measures are applied as a package in order from left to right. Measures appear to not be applied in order of cost-effectiveness (CE); however, they are applied as a package from left to right, with the order defined by their CE when modelled in isolation. The dashed reference line illustrates a social cost of carbon of \$31/ tCO_2eq, representing the economic cost to society caused by an additional tonne of CO_2eq emitted. Measures can be: (a) 'win-win', with potential to abate emissions and provide a private benefit (below the x-axis), (b) economically efficient, with potential to abate emissions at a cost less than the social cost of carbon (above the x-axis, but below the reference line) and (c) economically inefficient, with potential to abate emissions, but with a cost per tonne of carbon currently greater than the social cost of carbon (above both the x-axis and the reference line). FMD = foot and mouth disease; LSD = lumpy skin disease; GNC = groundnut cake.

emissions through improvements to productivity. This could be through the choice of breed, with those breeds with a higher level of productivity having lower Ei for protein production. However, the variation in Ei within breed groups with different levels of management input suggests that there is potential to abate emissions by improving the systems with the animals they currently rear. Results also demonstrate that breeds with a likely higher level of genetic potential for productivity do not always result in lower Ei. In particular, zebu cross herds with a comparable level of management input to zebu taurine cross herds (with a likely higher genetic potential for productivity (Table 1)), have a higher level of productivity and therefore a lower Ei. Due to challenging conditions, management input is important if production potentials are to be met. Crossbred animals that introduce increased productivity potential but retain some of the resilience of indigenous breeds are often more appropriate (Marshall *et al.*, 2016).

Key emission categories

The digestibility of feed rations will influence both enteric CH_4 and manure-related emissions (low digestibility increases enteric CH_4, and manure N and volatile solid excretion). Due to the high reliance on low quality roughages by these systems these emission categories are expected to be substantial; this is consistent with Opio *et al.* (2013). Cattle in these systems spend considerable time grazing pasture, depositing organic N in manure and urine, and any collected manure is stored solid, promoting the release of N_2O. Carbon dioxide from feed production contributes a higher proportion of total emissions than suggested by other studies for SSA (Opio *et al.*, 2013); this is due to the presence of processed feed components (GNC and PC) in the rations.

Abatement potential and cost-effectiveness

The effective control through vaccination of FMD and LSD, and the removal of Tryps burden through tsetse vector control, are consistent 'win-win' interventions (Table 5 and Figure 3). The cost of additional vaccination for effective protection is assumed to be outweighed by the expected increases in productivity and associated increases in household revenue (from increased milk yields and carcass weights). The removal of Tryps burden through the project explained by Bouyer *et al.* (2014), has an initial project cost, but then is followed by reoccurring annual productivity benefits (Table 3). Discounting the household revenue benefits over a period of 30 years provides a net present value that outweighs the project costs. A further refinement could be to allocate some of the cost to other benefits of removing the tsetse vector, such as expected health and production benefits for other livestock species and a reduction in grazing pressure (Bouyer *et al.*, 2014); this may increase the CE of tsetse removal further. The herd level productivity burdens (Table 3) of these shortlisted diseases are based on disease prevalence records, and are likely to be underestimated as disease occurrence is commonly under-reported by livestock keepers (Tebug *et al.*, 2015).

The improved timing of hay harvesting for optimal nutritional value is also suggested as a 'win-win' option (Table 5 and Figure 3). The improved nutritional value of hay improves the overall quality of the ration, and means less ration is required to meet the energy requirements of the cattle, representing reduced emissions and a cost reduction. It is assumed that improved hay will not increase in cost and will not require any additional labour. The CE, although always below \$0/tCO_2eq, varies between systems depending on the proportion of hay in the ration. The zebu taurine cross and taurine herds spend more time housed, so hay is a larger proportion of their ration (30% and 18%, respectively); therefore, this measure is most CE when applied to these systems. Both zebu taurine cross with a higher level of management and taurine herds also have a higher proportion of millet stover in their ration, making the urea treatment of stover a 'win-win' measure for these systems only.

In the current method, as ration digestibility is improved through nutritional mitigation measure application two variables change in the model. First, the ratio of net energy available in the ration for both maintenance and growth to digestible energy consumed increases. As no productivity increases are included in the model for nutritional improvements, the animal gross energy requirement decreases and there is a decrease in both feed intake and associated emissions. Second, with increasing ration digestibility the enteric CH_4 from each unit of feed consumed decreases. Therefore, the emissions AP and CE of the nutritional mitigation measures are derived from both reduced feed intake requirements and reduced enteric CH_4 emissions. Neither of these responses are linear, instead they follow a curve of diminishing returns; and nutritional measures that follow the application of previous nutritional measures will have less AP than if they were applied in isolation. For instance, although with substantial purchase costs, both GNC and PC greatly improve the digestibility of the ration. Groundnut cake is consistently more CE than PC when applied in isolation, therefore is applied first when part of a package. Purchased compound feed applied following the application of GNC has reduced AP and for both zebu taurine cross and taurine herds (which have a higher baseline ration digestibility than other groups), the AP of PC is outweighed by the increased emissions associated with its processing and transport (Table 5). This reveals a key limitation to the assessment of nutritional mitigation measures both within this study and when using the Tier 2 methodology. In reality when a ration is improved feed intake and animal productivity would likely increase, particularly for systems likely to be nutritionally limited (Bryan *et al.*, 2013). The emissions AP and CE of nutritional mitigation measures would then be a balance between productivity improvements, increasing both household revenue and units of produce over which to allocate emissions (reducing Ei); and an increase in feed intake, increasing emissions associated with feed and increasing the household feed costs.

It is encouraging that the results identify that 'win-win' measures are available, these are important for engagement and increased uptake of measures by livestock keepers. However, their presence raises a question as to why 'win-win' measures, such as the removal of FMD and LSD, are not currently adopted. Focus group discussions with over 200 of the study livestock keepers suggest barriers include: a lack of initial financial means to invest, a lack of regular access to resources, and system characteristics and traditions (Salmon *et al.*, 2016).

Conclusion

The results of this study suggest that the Ei of meat and milk from the study systems can be significantly reduced through measures that also maintain or increase protein production. A portion of this emission abatement could be achieved with apparent 'win-win' measures, improving the likelihood of essential engagement with livestock keepers. The study also reveals challenges, which deserve further investigation; in particular when using the Tier 2 methodology to assess the potential for nutritional measures. These include predicting the intake and productivity response of animals fed improved rations. Changes to feed intake could be estimated and the additional energy available to animals then used to predict productivity responses, however predicting the energy partitioning by cattle to different functions remains a challenge. Despite these challenges, the use of modelling to identify and quantify cost-effective measures of productivity improvement and GHG emission abatement, as demonstrated by this study, should be an important primary step in effective sustainable development efforts.

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Supplementary material

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