Mitigation of enteric methane emissions from ruminants in sub-tropical production systems

By

Cornelius Jacobus Lindeque du Toit

A thesis submitted in partial fulfilment of the requirements for the degree of:

PhD: Animal Science

In the

Faculty of Natural and Agricultural Sciences

Department of Animal and Wildlife Sciences

University of Pretoria

May 2017

Supervisory Committee

Prof W.A van Niekerk: Department of Animal and Wildlife Sciences
University of Pretoria
Private Bag X20
Hatfield
0028
South Africa

Prof L. J Erasmus: Department of Animal and Wildlife Sciences
University of Pretoria
Private Bag X20
Hatfield
0028
South Africa

Dr H.H Meissner: No 3, Die Hoewes
276 von Willich Street
Centurion
0157
South Africa

Declaration

I, Cornelius Jacobus Lindeque du Toit, declare that the thesis, which I hereby submit for the degree

PhD: Animal Science

At the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary intuition.

_____

Mr. C.J.L Du Toit

PhD Candidate

Acknowledgements

I would like to express my appreciation and thanks to my supervisors Professor W.A van Nierkerk, Dr H.H Meissner and Prof L.J Erasmus, who have been tremendous mentors to me. I would like to thank you for encouraging my research and for allowing me to grow as an animal scientist.

A special thanks to my family for all the sacrifices that they made on my behalf. I would also like to thank all my friends who supported and the staff at the university who assisted me with the trial work and sample analysis.

Preface

This thesis is based on the following chapters, which have been published or are submitted for publication in peer reviewed scientific journals.

1 Du Toit, C.J.L., Meissner, H.H and van Niekerk, W.A., 2013. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43, 320 – 339.

2 Du Toit, C.J.L., Meissner, H.H. and van Niekerk, W.A., 2013. Direct greenhouse gas emissions of the game industry in South Africa. S. Afr. J. Anim. Sci. 43, 376 – 393.

3 Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013. Direct methane and nitrous oxide emissions of monogastric livestock in South Africa. S. Afr. J. Anim. Sci. 43, 362 – 375.

4 Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013. Direct greenhouse gas emissions of the South African small stock sectors. S. Afr. J. Anim. Sci. 43, 340 – 361.

5 Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L. J. and Morey, L., 2016. Nutrient composition and *in vitro* methane production of tropical grass species in transitional rangeland of South Africa *(Submitted to the Rangeland Journal October 2016).*

6 Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L. J. and Morey, L., 2017. *In vitro* total and methane gas production of common South African improved sub-tropical and temperate grass species as influenced by nitrogen fertilization (*submitted for publication to Scientia Agricola, May 2017).*

7 Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L. J. and Coertze, R.J, 2017. Methane emissions from sheep fed *Eragrostis curvula* hay substituted with *Lespedeza cuneata (submitted for publication to the Journal of Arid Environments, May 2017).*

Enteric methane emissions contribute to climate change and present an opportunity to increase efficiency gains in livestock production systems by reducing the amount of gross energy intake lost as methane. Livestock is a major contributor to greenhouse gas emissions globally and contributes 90% of the South African agricultural sector's methane emissions. The development of accurate greenhouse gas emission factors from South African livestock production systems will enable researchers to develop decision support models which can form part of greenhouse gas mitigation strategies and evaluation of such mitigation strategies.

The main objectives of this PhD study were to develop country specific greenhouse gas emission factors for South African livestock on a Tier 2 level and to identify possible mitigation strategies for extensive livestock production systems. The research was conducted in the Department of Animal and Wildlife Sciences, Faculty of Natural and Agricultural Sciences at the University of Pretoria, South Africa. To accomplish the objectives a modified International Panel on Climate Change methodology adapted to conditions similar to South African livestock production conditions were followed to calculate country specific Tier 2 emission factors. Extensive livestock production systems are rangeland and pasture based and the methanogenic potential of a range of grass species under natural rangeland and improved pasture production systems were evaluated through *in vitro* techniques. The effect of substituting *Eragrostis curvula* hay with *Lespedeza cuneata* hay as a possible methane mitigation strategy for extensive ruminant production systems was also evaluated using sheep in an *in vivo* study.

Mitigation of enteric methane emissions from ruminants in sub-tropical production systems

by

Cornelius Jacobus Lindeque du Toit

Supervisor: Prof W.A. van Niekerk

Co-supervisor: Prof L. J. Erasmus

Co-supervisor: Dr H. H. Meissner

Department of Animal and Wildlife Sciences

Faculty of Natural and Agricultural Sciences

University of Pretoria

South Africa

Degree: PhD (Animal Science)

Executive summary

Globally agriculture and livestock producers have come under increasing pressure over the environmental impact of production systems. The objectives of this study were to re-calculate the direct methane (CH_4) and nitrous oxide (N_2O) emissions of livestock production systems in South Africa, taking into consideration the uniqueness of the South African scenario and to identify and evaluate possible greenhouse gas mitigation strategies for extensive production systems. It is important to generate accurate greenhouse gas (GHG) baseline figures to develop South Africa's capacity to understand and reduce GHG emissions emitted from the livestock sector.

Livestock produce GHG's in the form of methane from enteric fermentation and nitrous oxide and methane from manure management and manure deposited on pastures and rangeland by grazing animals. Agriculture, forestry and land use (corrected for carbon sink values) emitted an estimated 4.9% of South African GHG gases in 2004, which makes it the third largest GHG contributor in South Africa after the energy industry and industrial processes. Livestock produced approximately 27% of the national methane emissions and 98% of the agricultural sector's methane emissions in 2004.

Methane is a potent GHG that remains in the atmosphere for approximately 9 to 15 years and is 28 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2) over a 100-year period. Nitrous oxide has an atmospheric lifetime of 150 years and a global warming potential of 265 times that of CO_2 over a 100-year period.

South African livestock production is based on a unique combination of commercial (intensive and extensive) and emerging and communal (subsistence) production systems. The levels of productivity and efficiency in these production systems vary greatly in certain areas and it is important to distinguish between them when calculating GHG emissions. Previous inventories were conducted on a national scale utilizing IPCC default values (Tier 1 approach) for some or all of the emission calculations. These emission factors do not distinguish effectively between classes of animals, production efficiencies, and production systems. They are often based on assumptions of animals utilizing diets which are not representative of South African production systems.

The IPCC Tier 2 methodology seeks to define animals, animal productivity, diet quality and management circumstances to support a more accurate estimate of feed intake for use in estimating methane production from enteric fermentation. It was also considered important to do separate calculations for each province as provinces differ in vegetation or biomes and production systems which may require different approaches to mitigation recommendations. Due to the heterogeneity of available feed types within South Africa it was considered important to use methodologies that could reflect such differences and was developed under similar conditions.

The methodology utilized is based on the Australian national greenhouse account's National Inventory Report, which contains Australian country-specific and IPCC default methodologies and emission factors. Emission factors specific to South African conditions and management systems were calculated where possible. A Tier 2 approach was adopted for all major livestock categories including privately owned game in accordance with the IPCC Good Practice requirements. Recently game farming has become a recognized commercial enterprise in the agricultural sector which needs to be included as an anthropogenic emissions source.

Methane emissions from South African livestock were estimated at 1328 Giga gram (Gg) during 2010. Dairy and beef cattle contributed an estimated 964 Gg or 72.6% of the total livestock methane emissions in South Africa during 2010. Beef cattle in extensive systems were the largest contributor (83.3%), followed by dairy cattle (13.5%), and feedlot cattle (3.2%). The estimated direct enteric methane emission factors for dairy and beef cattle were higher than the IPCC default factors for Africa. The Eastern Cape recorded the highest dairy and beef cattle methane emissions, whereas Gauteng showed the highest feedlot methane emissions primarily due to cattle numbers.

Small stock was responsible for 15.6% of the total livestock emissions contributing an estimated 207.7 Gg, with sheep producing 167 Gg and goats producing 40.7 Gg. Calculated enteric methane emission factors for both commercial and communal sheep were higher than the IPCC default values for developing countries. A similar tendency was found with goat emission factors. The highest sheep and goat methane emissions were reported for the Eastern Cape province.

The pig and ostrich industry both contributed approximately 8 Gg CH_4 during 2010. The North-West province produced the highest commercial pig GHG emissions with the highest communal pig emissions originating from the Eastern Cape. The poultry industry was the largest direct N_2O producer of the non-ruminant livestock industries, contributing 2.3 Gg or 92.8% of the total non-ruminant N_2O emissions.

The privately owned game industry contributed an estimated 131.9 Gg of methane emissions with the provinces of Limpopo, Eastern Cape and Northern Cape being the three largest contributors with 43.4, 37.3 and 21 Gg methane, respectively. The total privately owned game population was estimated at 2 991 370 animals, utilizing 20.5 million hectares.

Beef cattle are the major contributors to livestock GHG emissions in South Africa followed by sheep, privately owned game, dairy cattle, goats, pigs, ostriches, equine, and poultry. The IPCC default values for Africa underestimate emission factors across all livestock categories. The methane

emission factors calculated for commercial livestock production systems are more comparable to emission factors from developed countries and the emerging/communal production systems to those of developing countries. This emphasizes the need to develop country-specific emission factors through quantitative research for livestock in all provinces and on all types of production systems to produce accurate baseline figures, which is critical to future mitigation protocols.

As part of this study fourteen tropical grass species typical of transitional rangeland regions of South Africa were characterised in terms of chemical composition, *in vitro* total gas and *in vitro* methane production. The results of the study demonstrated that *in vitro* methane production varied between tropical grass species typical of transitional rangeland in South Africa. The variation between species allows for the potential to identify and select species with a lower enteric methane production potential. *Panicum maximum*, *Eragrostis curvula* and *Elionurus miticus* were the three species which produced the lowest *in vitro* methane production but which also had a crude protein (CP) concentration of more than 3.5% of dry matter (DM) and with an *in vitro* organic matter digestibility (IVOMD) above the group average for the study. Furthermore, the results of the study revealed that *in vitro* methane production was higher in Decreaser species compared to Increaser species.

Improving the quality of available forages through the use of cultivated pastures and fertilization is known to improve ruminant production efficiency. The effect of level of nitrogen (N) fertilization on certain qualitative parameters and *in vitro* total gas and methane production of improved grass species commonly utilised in South Africa was evaluated. Treatments included seven grass species divided into two photosynthetic pathways (C3 and C4) with three levels of N fertilization (0, 50 and 100 kg N/ha). No effect was found for N fertilization on *in vitro* total gas or methane production. The CP concentration increased ($P < 0.05$) and the NDF concentration tended to decrease ($P < 0.1$) as the level of N fertilization increased for both C3 and C4 species. Increasing the level of N fertiliser increased ($P < 0.05$) the methanogenic potential of *Dactylis glomorata*, *Festuca arundinacea* and *Cenchrus ciliaris* after the 24 hour incubation period but no effects ($P>0.05$) were found after the 48 hour incubation period. Results suggests that the stage of physiological development of forages might have a greater influence on the methanogenic potential of forages compared to the effect of N fertiliser application.

Finally, the effect of feeding *Lespedeza cuneata* hay, containing condensed tannins (CT), at different levels on the DM feed intake and methane emissions of sheep fed a basal diet of *E. curvula* hay was investigated as a possible mitigation strategy. The study was conducted *in vivo* using open circuit respiration chambers. Results suggested that *L. cuneata* had the potential to reduce CH_4 emission from sheep fed a sub-tropical hay based diet in addition to possible improved production. Substituting *E. curvula* hay with 60% *L. cuneata* on a DM basis resulted in a 21.4% reduction in CH_4 emissions compared to a solely *E. curvula* diet.

Thesis outputs

Scientific publications:

Peer-reviewed journals

Du Toit, C.J.L., Meissner, H.H and van Niekerk, W.A., 2013. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S.Afr. J. Anim. Sci. 43, 320 – 339.

Du Toit, C.J.L., Meissner, H.H. and van Niekerk, W.A., 2013. Direct greenhouse gas emissions of the game industry in South Africa. S.Afr. J. Anim. Sci. 43, 376 – 393.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013. Direct methane and nitrous oxide emissions of monogastric livestock in South Africa. S.Afr. J. Anim. Sci. 43, 362 – 375.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013. Direct greenhouse gas emissions of the South African small stock sectors. S.A. J. Anim. Sci. 43, 340 – 361.

Peer-reviewed publications not included in the thesis

Du Toit, C.J.L., van Niekerk, W.A. and Meissner, H.H., 2013. Methane emissions of the South African sheep industry. Adv. Anim. Biosci. Vol. 4: 558.

Ogle, S.M., Spencer, S., Hartman, M., Buendia, L., Stevens, L., **du Toit, C.J.L**. and Witi, J., 2016. Developing national baseline GHG emissions and analysing mitigation potentials fot agriculture and forestry using an advanced national GHG inventory system. Adv. Agric. Syst. Modelling 6, 129 – 148.

Articles submitted to peer-reviewed publications included in the thesis

Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L.J. and Morey, L., 2017. Nutrient composition and *in vitro* methane production of sub-tropical grass species in transitional rangeland of South Africa. Submitted to the Rangeland Journal (Ref: RJ16099).

Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L.J. and Morey, L., 2017. *In vitro* and methane gas production of common South African improved sub-tropical and temperate grass species as influenced by nitrogen fertilization. Submitted to Scientia Agricola (Ref: SA-2017-0181).

Du Toit, C.J.L., Van Niekerk, W.A., Meissner, H.H., Erasmus, L.J. and Coertze, R.J., 2017. Methane emissions from sheep fed *Eragrostis curvula* hay substituted with *Lespedeza cuneata*. Submitted to the Journal of Arid Environments (Ref: JAE 17-273).

Conferences:

International

Du Toit, C.J. L., van Niekerk, W.A., Meissner, H.H and Van Wyngaard, J., 2016. Direct greenhouse gas emissions from South African livestock industries. Greenhouse gases and animal agriculture, Melbourne, Australia, February 2016.

Du Toit, C.J.L., van Niekerk, W.A, and Meissner, H.H., 2013. Methane emissions of the South African sheep industry. Greenhouse gases and animal agriculture, Dublin, Ireland, June 2013.

Du Toit, C.J.L., Meissner, H.H. and van Niekerk, W.A., 2012. Methane emissions of the South African Dairy industry. World Dairy Summit, Cape Town, 2012.

National

Du Toit, C.J.L. and Van Niekerk, W.A., 2014. Potential of mitigating methane and nitrous oxide emissions from Southern African ruminant production systems. Young Researcher Symposium, Facing Environmental Challenges, South Africa, August 2014.

Technical publications:

Du Toit, C.J.L., 2015. Reducing enteric methane emissions from ruminants. Technical report to the Red Meat Research and Development Trust project committee.

Stevens, L., **Du Toit, C.J.L**. and Witi, J., 2013. Agriculture, Forestry and Land use. In: GHG Inventory for South Africa: 2000 – 2010. Department of Environmental Affairs, South Africa. http://www.saaqis.org.za

Popular publications:

Du Toit, C.J.L., 2017. Grazing efficiency key tool in reducing carbon emissions. Red Meat/ Rooivleis 8 (1), 74 – 79.

Du Toit, C.J.L., 2011. Cut the gas. Red Meat/ Rooivleis, 2 (2), 52 – 53.

Table of Contents

Contents

List of Tables

List of abbreviations

ADF	:	Acid detergent fibre
ADG	:	Average daily gain
ADL	:	Acid detergent lignin
ADIN	:	Acid detergent nitrogen
ANOVA	:	Analysis of variance
ATP	:	Adenosine triphosphate
BW	:	Body weight
C3	:	Temperate plants with a three carbon photosynthetic pathway
C4	:	Tropical/sub-tropical plants with a four carbon photosynthetic pathway
C	:	Carbon
Ca	:	Calcium
CH_4	:	Methane
C_2H_6	:	Ethane
CO_2	:	Carbon dioxide
CP	:	Crude protein
DM	:	Dry matter
DMI	:	Dry matter intake
DMD	:	Dry matter digestibility
DOM	:	Digestible organic matter
DOMI	:	Digestible organic matter intake
EE	:	Ether extract
FME	:	Fermentable metabolisable energy
Gg	:	Giga gram
H	:	Hydrogen
H_2S	:	Hydrogen sulfide
IVOMD	:	*In Vitro* organic matter digestibility

L	:	Litre
LMD	:	Laser methane detector
ME	:	Metabolisable energy
mg	:	Milligram
Mg	:	Magnesium
MJ	:	Mega joule
mM	:	Millimolar
MP	:	Metabolisable protein
N	:	Nitrogen
NADH	:	Nicotinamide adenine dinucleotide hydride
NDF	:	Neutral detergent fibre
NFC	:	Non-fibrous carbohydrates
NI	:	Nitrogen intake
NO_3^-	:	Nitrate
NPN	:	Non-protein nitrogen
O_2	:	Oxygen
OM	:	Organic matter
OMD	:	Organic matter digestibility
OMI	:	Organic matter intake
P	:	Phosphorus
PEP	:	Phosphoenolpyruvate
PO_4^{3-}	:	Phosphate
RFI	:	Relative feed intake
S	:	Sulphur
SEM	:	Standard error of mean
TMR	:	Total mixed ration
VFA	:	Volatile fatty acid

General Introduction

The agricultural sector is currently faced with the challenge of feeding a growing population predicted to peak at 9 billion people by 2050 (FAO, 2010), whilst meeting social and environmental obligations to reduce the environmental impact of production systems (Meale, 2012). The demand for livestock products will be driven by changes in population size and improvement of social capital, particularly in developing countries. Livestock production is implicated as a significant source of greenhouse gas (GHG) emissions producing methane (CH_4) and nitrous oxide (N_2O). Both these are potent GHG's with 28 and 265 the global warming potential (GWP) of carbon dioxide (CO_2) over a 100-year atmospheric life cycle (IPCC, 2014).

Livestock produced approximately 27% of the total South African methane emissions during 2004 and 98% of the agricultural sector's methane emissions (Otter, 2010). The Intergovernmental Panel on Climate Change (IPCC) stipulates national inventory methods to record agricultural sector emissions and implicitly the share of different subsectors in the total sector. Emission estimates from the agricultural sectors are subject to much uncertainty. Generic emission coefficients are commonly used (IPCC Tier 1) which do not consider the differences in production systems and efficiencies between species, production systems and regions.

South African livestock production is based on a unique combination of commercial (intensive and extensive), emerging and communal (subsistence) production systems. The levels of productivity and efficiency in these production systems vary greatly in certain areas and it is important to distinguish between them when calculating GHG emissions. Several factors influence methane production from livestock including population numbers, the size and productivity of animals, level of feed intake, diet composition, digestibility and quality of forage, forage species and cultivar, as well as variation amongst animals (Scholtz *et al*., 2012).

Accurate data on GHG emissions from all livestock sectors are crucial to develop and evaluate country specific mitigation strategies and to identify key emission sources within the livestock sector. Previous livestock GHG inventories (Blignaut *et al*., 2005; Otter, 2010) were conducted on a national scale utilizing IPCC default values (Tier 1 approach) for some or all of their emission calculations. These emission factors do not distinguish effectively between classes of animals, production efficiencies, and production systems. They are often based on assumptions of animals utilizing highly digestible diets as well as temperate forages (Mills *et al*., 2001) which are not representative of South African production systems. It is important to generate accurate GHG baseline figures to develop South Africa's capacity to understand and reduce GHG emissions from the livestock sector.

This research is timely considering international discussions and negotiations around how agriculture should be included in efforts to reduce greenhouse gas emissions and adapt to climate change impacts. Recently, South Africa committed to greenhouse gas reduction targets below business as usual of 34% by 2020 and 42% by 2025 (DEA, 2015). The agricultural sector must improve efforts to reduce GHG emissions keeping in mind food security for an ever-growing population. Population growth and shifts in dietary patterns towards more livestock products will lead to increased livestock emissions unless producers improve production efficiency and

management (Gerber *et al*., 2013).

Approximately 70% of the surface area available to farming in South Africa is only suitable for extensive farming with beef cattle, small stock, and game (Scholtz *et al*., 2012). O'Mara (2011) stated that livestock GHG emissions relate closely with ruminant numbers, particularly cattle. During 2004, commercial beef cattle contributed 45% and emerging/communal cattle 33% of the total enteric fermentation of 1225 Giga gram (Gg) CH_4 in South Africa (Otter, 2010). Poor nutritional conditions characterized by highly lignified, low digestible feed from poor and often nitrogen (N) limited native rangeland and crop residues limit the productivity of livestock in tropical and sub-tropical regions (Goel and Makkar, 2012). Ruminants fed on low quality forages represent a significant loss of dietary energy to CH_4 production that could potentially be redirected towards the production of milk, meat and fibre (Eckard *et al*., 2010).

Understanding the effect of forage quality on the production of anthropogenic GHG from livestock is important for the development of mitigation strategies in livestock production systems. Significant variability in the *in vitro* rumen fermentation characteristics and methanogenic potential among forage species have been identified by Durmic *et al*. (2010). These differences have potential to be exploited to improve the forage quality offered to livestock while also contributing to improved environmental sustainability. Improving forage quality through selection, rangeland reinforcement and improved management systems has the potential to reduce CH_4 emissions per unit animal product because of increased digestibility and reduced ruminal retention time of feed particles (Hristov *et al*., 2013). Nitrogen fertilization has been shown to influence the pattern of crude protein (CP) and neutral detergent fibre (NDF) degradation in the rumen (Valk *et al*., 1996) which could influence the methanogenic potential of forages. *In vitro* fermentation has been proven to be a practical method for screening of forage fermentation characteristics and methanogenic potential (Durmic *et al*., 2010) and it can be used to predict CH_4 production from ruminal fermentation of plant material (Johnson and Johnson, 1995).

This dissertation presents results and comprehensions from my PhD study based on seven papers. The overall aim has been to develop country specific (IPCC Tier 2) CH_4 and N_2O emissions factors for the South African livestock industry including commercially farmed game on a provincial basis and to identify practical mitigation strategies for extensive livestock production systems in South Africa.

References

Blignaut, J.N., Chitiga-Mabugu, M.R. and Mabugu, R.M., 2005. Constructing a greenhouse gas inventory using energy balances: the case of South Africa 1998. J. Energy S. Afr. 16, 21-32.

DEA, 2015. Department of environmental affairs: South Africa's intended nationally determined contributions (INDC) – discussion document. Pretoria, South Africa.

Durmic, Z., Hutton, P., Revell, D., Emms, J., Huges, S., and Vercoe, P. (2010). *In vitro* fermentation traits of Australian woody perennial plant species that may be considered as potential sources of feed for grazing ruminants. Anim. Feed Sci. Tech. 160, 98 – 109.

Eckard, R.J., Grainger, C., and De Klein, C.A.M. (2010). Options for abatement of methane and nitrous oxide from ruminant production. Livest. Prod. Sci. 130, 47 – 56.

FAO, 2010. Food and Agriculture Organization of the United Nations, 2010. [Accessed on 5 March 2012]. FAOSTAT.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G., 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Goel, G., and Makkar, H.P.S. (2012). Methane mitigation from ruminants using tannins and saponins, a status review. Trop. Anim. Health and Prod. 44, 729 – 739.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adegosan, A.T., Yang, W., Lee, c., Gerber, P.J., Henderson, B. and Tricarico, J.M., 2013. Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91, 5045 – 5069.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483 – 2492.

Meale, S.J., Chaves, A.V., Baah, J., and McAllister, T.A. (2012). Methane production of different forages in *in vitro* ruminal fermentation. Asian-Aust. J. Anim. Sci. 25 (1), 86 – 91.

Mills, J.A., Dijkstra, J., Bannik, A., Cammell, S.B., Krebreab, E. and France, J., 2001. A mechanistic model of whole tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation and application. J. Anim. Sci. 79, 1584-1597.

O'Mara, F.P., 2011. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Anim. Feed Sci. Technol. 166-167, 7-15.

Otter, L., 2010. The South African agricultural GHG inventory for 2004. Department of Agriculture, Forestry and Fisheries, South Africa.

Scholtz, M.M., Steyn, Y., Van Marle-Koster, E. and Theron, H.E., 2012. Improved production efficiency in cattle to reduce their carbon footprint for beef production. S. Afr. J. Anim. Sci. 42, 450-453.

Valk, H., Kappers, I.E. and Tamminga, S. 1996. *In sacco* degradation characteristics of organic matter, neutral detergent fibre and crude protein of fresh grass fertilised with different amounts of nitrogen. Anim. Feed Sci. Tech. 63, 63 – 87.

Chapter 1

Review of literature

Introduction

The emissions of greenhouse gases and their contribution to global climate change have been the subject of many studies in recent years (Johnson and Johnson, 2002; Moss *et al.*, 2000; Boadi *et al.*, 2004; Kebreab *et al.*, 2006; Caro *et al.*, 2017). Methane emissions play a critical role in global warming as it has a global warming potential 28 times that of CO_2 (Xu *et al.*, 2017). From all methane emissions sources, agriculture is by far the most important source in South Africa. Enteric fermentation in ruminants accounts for 90% of the agricultural sectors methane emissions (Blignaut *et al.*, 2005).

The aim of this literature review is to give a basic understanding of methane production from ruminants, outline the impact of enteric methane emissions on global climate change, to describe the various factors that can influence enteric methane production and to describe the techniques used for measuring and predicting methane emissions from livestock. Possible ways to reduce methane emissions from livestock are also discussed.

Overview of global warming

Evidence of global warming

The United Nations Framework Convention on Climate Change (UNFCCC) has defined climate change as "a change in climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability" (UNFCCC, 2006). Increasing atmospheric temperatures above historical levels have been observed during the past 30 – 50 years, and no "natural" causes for the warming have been confirmed (Hope *et al.*, 2017). Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (IPCC, 2007). The global increases in carbon dioxide concentrations are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agricultural activities (IPCC, 2007). The UNFCCC reported an expected increase in global temperatures of 1.8 to 4°C by 2100 (IPCC, 2007).

Indications of warming include increases in atmospheric water vapor, increases in land surface (0.27°C per decade) and ocean (0.13°C per decade) temperatures, glaciers shrinking, reduced snow falls and a significant reduction in the extend of Arctic sea-ice (2.7% per decade since 1978) (Solomon *et al.*, 2007; Vlaming, 2008). The accumulation of greenhouse gases (GHG) in the atmosphere, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) is contributing to the increase in the earth's temperature (Moss *et al.*, 2000; Boadi *et al.*, 2004). The increase in the atmospheric concentrations of these three gases from the pre-industrial era to 2005 are 280 to 379 ppm for CO_2, 715 to 1774 ppb for CH_4 and 270 to 319 ppb for N_2O (Vlaming, 2008). Xu *et al.* (2017) reported the global warming potential (GWP) of CH_4 to be 28-fold greater than that of CO_2 and that of N_2O 265-times greater than CO_2.

Mechanisms of global warming

Solar radiation drives the earth's weather and climate, and heats the earth's surface. In turn, the earth radiates energy back into space. Outgoing radiation from the earth's surface is partially absorbed by some atmospheric gases (water vapor, CO_2, CH_4, N_2O and others) and then re-emitted to the surrounding atmosphere (Moss *et al.*, 2000). This traps some of the outgoing energy, retaining heat similar to the panels of a greenhouse.

Greenhouse gases in the atmosphere are essential for maintaining life on earth, as without the greenhouse effect the planet would be permanently frozen because all incoming heat from the sun would be radiated back into space by the earth's surface (Moss, 1993). Global warming is caused by extra heat being trapped and re-emitted to the atmosphere by increased concentrations of GHG due to human activity (Vlaming, 2008).

Methodological approach of the International Panel on Climate Change

The IPCC apply a tiered approach to GHG emissions estimation according to the availability of required activity data. Each tier represents a level of methodological complexity. Tier 1 is the basic method utilizing IPCC recommended country default emission factors irrespective of variations in animal physiological state and production level. Tier 2 and 3 methodologies are more demanding in terms of complexity and data requirements. Tier 2 requires an intermediate level of complexity and country specific data to estimate emission factors. Tier 3 requires the most specific data and utilises country specific emission factors measured and developed through experimentation. Progressing from Tier 1 to Tier 3 generally represents a reduction in the uncertainty of GHG estimates at a cost of an increase in the complexity of measurement processes and analysis.

Greenhouse gas production in South Africa

Africa is one of the most vulnerable continents to climate change and climate variability (Boko *et al.*, 2007). South Africa appears already to be experiencing the early effects of global warming and climate variability. The average land and sea temperatures have increased, sea level is rising, rainfall patterns have changed, and the intensity and frequency of extreme weather events have increased (Ziervolgel *et al.*, 2014).

South Africa ranks among the world's top 12 largest CO_2 emitters (Wolpe and Reddy, 2015). South Africa's emissions *per capita* are higher than China and India and are approximately 4.7 t CO_2-equivalanets higher than the global average (DEAT, 2007). The overall increase in CO_2-equivalent concentration is approximately 0.6% per year in South Africa. The DEA (2014) predicted a quadruple increase in CO_2-equivalent emissions by 2050 form 440 Mt to 1600 Mt. South Arica, under the Copenhagen Accord, committed to GHG reduction targets of 34% from business as usual by 2020 and of 42% by 2025 (DEA, 2015). This is accordance with the requirements of the Kyoto protocol of which South Africa is a signatory.

The South African agricultural sector, excluding forestry and other land use, is the second highest contributor to the national CO_2-equivalent emissions after the energy sector (DEA, 2014), contributing 48% to national CH_4 emissions and 78% of the national N_2O emissions. Livestock

contributes approximately 65% of the agricultural GHG emissions (CO_2-equavalent) of which enteric fermentation accounts for 90% (Meissner *et al.*, 2012).

Vulnerability of South Africa to climate variability.

Climate change poses a significant threat to South Africa's water resources, food security, health, infrastructure, ecosystems, and biodiversity (Montmasson-Clair and Zwane, 2016). Climate projections in South Africa over the next 50 years indicate that the western parts of the country will become dryer, with shorter rainfall seasons in certain areas and with increased surface temperatures in the interior (Hosu *et al.*, 2016). Impacts of climate change on the South African agricultural sector indicates that crop net revenues will likely fall by as much as 90% by 2100, with small-scale farmers being the most severely effected (Boko *et al.*, 2007).

South Africa's rainfall is highly variable both within and between years. Much of the country is arid or semi-arid and the whole country is subject to droughts and floods. A reduction in the amount or reliability of rainfall as predicted by van Jaarsveld and Chown (2001), or an increase in evaporation will exacerbate the already serious lack of surface and ground water in the country (Hosu *et al.*, 2016). Van Jaarsveld and Chown (2001) predicted that with a doubling in atmospheric CO_2 levels the arid interior and moister north-eastern regions of South Africa are likely to be subjected to elevated evapotranspiration rates, increased stress, and more frequent flood events, whereas the south-western regions of the country are likely to experience increased early winter frontal and orographical rainfall. Desertification, which is already a problem in South Africa, could also be exacerbated by climate change (DEAT, 2004).

Seventy percent of the land surface of South Africa consists of natural and semi-natural ecosystems which provide rangelands for herbivore species (DEAT, 2004). Models run by the Department of Environmental Affairs of South Africa suggest a general aridification of this land type, especially where such rangelands are already marginal. Increases in temperature and CO_2 concentrations could cause an increase in bush encroachment into the grassland areas which would have a negative effect on fodder production. Van Jaarsveld and Chown (2001) suggested that the savanna component of rangelands is more sensitive to the predicted changes in temperature and rainfall and decreases of up to 20% in forage production are likely in savanna regions.

Crop yield modelling over the next 50 years predicts a 20% reduction in maize production. This reduction is associated with elevated temperatures or reduced water availability (van Jaarsveld and Chown, 2001; DEAT, 2004). Speciality crops grown in specific environmentally favourable areas may also be at risk, since both rainfall and temperature effects may cause significant changes in areas uniquely suitable for such specialized production (Stige *et al.*, 2006). An increase in pests and diseases would also have a detrimental effect on the agricultural sector and invasive plants could become a greater problem (Bett *et al.*, 2017).

Areas considered climatically suitable for South Africa's seven existing terrestrial biomes could shrink by between 40 and 55% over the next 50 years (van Jaarsveld and Chown, 2001). These authors argue that a doubling in atmospheric CO_2 concentrations would mean the complete loss of the succulent Karoo biome, which is the world's largest succulent flora and arguably the world's most botanically diverse arid region (Cowling *et al.*, 1998). Forty four percent of plant and 80% of animal species could undergo some, usually marked, alterations to their geographic ranges with a doubling of atmospheric CO_2 concentrations by 2050 (Simmons *et al.*, 2004). The majority of range shifts in both plants and animals were predicted to take place in an easterly direction towards the eastern

highlands of South Africa, a pattern in keeping with the predictions of significant increases in aridity in the western parts of the country and less intense aridification towards the east (van Jaarsveld and Chown, 2001; DEAT, 2004).

Ruminant methane production

Digestion in the rumen

Ruminants rely on a process of microbial fermentation to convert ingested plant material into absorbable end products to meet their nutritional requirements. Symbiotic microbes in the animal's reticulo-rumen and large intestine hydrolyse plant polysaccharides to simple sugars, with the end products of fermentation being volatile fatty acids (mainly acetic, propionic, and butyric acid), ammonia, methane, and microbial cells (Hobson, 1997).

The rumen is essentially a fermentation vat, containing a variable amount of digesta (4-7 kg in sheep and 50-80 kg in dairy cattle), of which 80 to 90% is fluid (Tamminga *et al.*, 2007). The high moisture content and a semi constant temperature of 37°C and pH of 5.5-6.5 make the rumen an immensely suited environment for microbes to survive and grow, provided that the microbes are regularly supplied with a suitable substrate. Substrates needed by the microbes are provided through the ingestion of feed (Tamminga *et al.*, 2007). Ruminal pH is kept within a constant range through the buffering capacity of saliva containing bicarbonate and phosphates (O'Hara *et al.*, 2003).

Site of methane production and release

Enteric methane is produced through microbial fermentation of the diet mainly in the reticulo-rumen (rumen) with a smaller amount in the large intestine (O'Hara *et al.*, 2003). Murray *et al. (*1976) conducted an isotope experiment on sheep fed lucerne chaff and found that 13% of the CH_4 was produced in the lower digestive tract, whereas Torrent and Johnson (1994) reported 8 – 13% of total CH_4 production of sheep fed cracked corn or grain based diets was produced in the large intestine.

Murray (1976) and Vlamming (2008) reported that the routes of methane release were by eructation (83%), breath (16%) and through the anus (1 – 2 %), these authors also reported that approximately 89% of the CH_4 produced in the large intestine was absorbed into the blood and released into the lungs.

Microbial synthesis of methane in the rumen

The anaerobic conditions in the rumen and hindgut limit oxidation of organic substrate into carbon dioxide and water, but an internal arrangement of the carbon, hydrogen, and oxygen present in the feed, between the microbial biomass and the end products of fermentation, keeps the system functioning (Tamminga *et al.*, 2007). Although H_2 is one of the major end products of fermentation by protozoa, fungi, and some bacteria, it does not accumulate in the rumen because it is immediately utilized by other bacteria which are present in the mixed microbial ecosystem (Moss *et al.*, 2000). The collaboration between fermentation species and H_2-utilizing bacteria (e.g. methanogens) is called "interspecies hydrogen transfer" (Wolin *et al.*, 1997).

Methanogens are a specialized group of micro-organisms that are not true bacteria, but they are a sub-group of the *archaea* which are widely distributed in nature (O'Hara *et al.*, 2003). Jarvis *et al*. (2000) isolated some of the ruminal methanogens and found *Methanobrevibacter* and *Methanomicrobium* in

large numbers and smaller numbers of *Methanosarcina*. Methanogens facilitate the processes, such as cell wall degradation, by preventing the accumulation of hydrogen (NADH) through a series of biochemical reactions. These biochemical reactions are shown in figure 1.1.

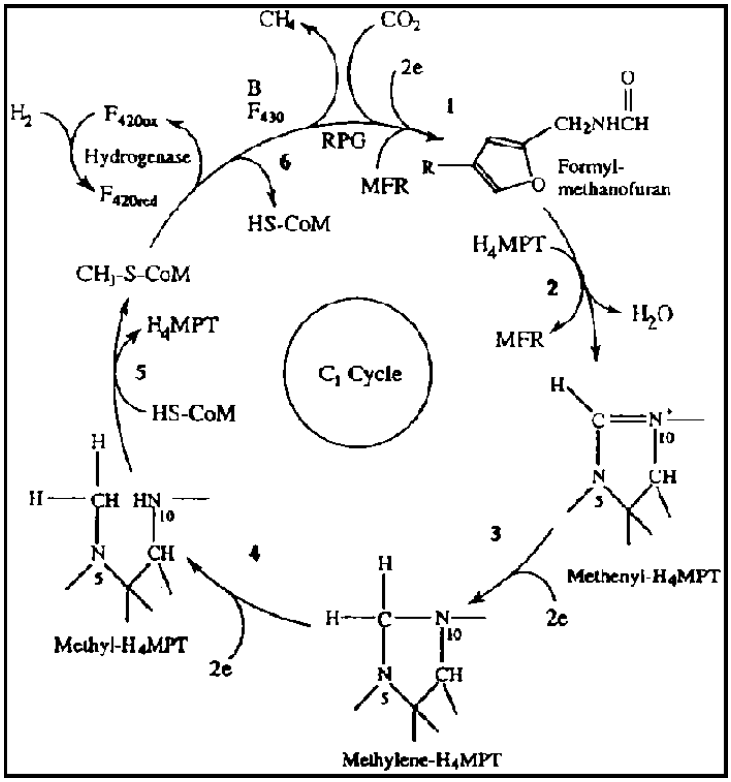

Figure1.1 Proposed cycle for the reduction of CO_2 to CH_4 (Rouviere and Wolfe, 1988).

The process of interspecies hydrogen transfer results in an increased carbon turn-over, greater production of oxidized end-products, increased growth of organisms and maximal energy yield per gram of fermented organic matter (Wolin *et al.*, 1997).

The physical association between fermentative species and H_2-users may facilitate inter species transfer in the rumen (Moss *et al.*, 2000) and attachment of methanogens to the external pellicle of protozoa has been reported by Stumm *et al*. (1982). Hegarty (1999) reported that up to 37% of ruminal methane emission could originate from the microbes living on and in protozoa. One important consequence of hydrogen utilization by methanogens is the maintenance of a low partial pressure of hydrogen in the rumen (O'Hara *et al.*, 2003). If hydrogen accumulated in the rumen, the re-oxidation of NADH would be inhibited, reduced fermentation end-products such as lactate would accumulate and forage digestion and microbial growth would be reduced (O'Hara *et al.*, 2003).

The formation of methane is one of the major H_2 sinks through the following reaction:
$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$

Metabolic hydrogen in the form of reduced protons (H) can also be used during the synthesis of volatile fatty acids or incorporated into microbial organic matter (Moss *et al.*, 2000). The stoichiometry of the main anaerobic fermentation pathways can be summarized as follows:

2H producing reactions:

Glucose → 2 pyruvate + 4H
(Embden-Meyerhof-Parnas pathway)
Pyruvate + H_2O → Acetate (C2) + CO_2 + 2H

2H using reactions:

Pyruvate + 4H → Propionate (C3) + H_2O
2 C2 + 4H → Butyrate (C4) + $2H_2O$
CO_2 + 8H → Methane (CH_4) + $2H_2O$

Moss *et al*. (2000) stated that the molar percentages of volatile fatty acids influences the production of methane in the rumen. Acetate production promote methane production while propionate and valerate formation can be considered as a competitive pathway for hydrogen use in the rumen. Acetate is the main volatile fatty acid resulting from rumen fermentation of fibre, starch, sugars, and protein (Bannink *et al.*, 2006) and therefore a net excess of H_2 is produced in the rumen. Tamminga *et al*. (2007) identified other H_2 sinks in the rumen such as microbial synthesis with NH_3 as the N source and the biohydrogenation of unsaturated fatty acids. The type of volatile fatty acids produced during fermentation is the major determinant of the amount of H_2 produced in the rumen.

Factors influencing enteric methane production

According to Bannink (2007) factors that can be identified as influencing CH_4 yield include dietary characteristics as well as the fermentation conditions in the rumen. These dietary characteristics include daily feed intake and rumen fill, the proportion of concentrates in the dietary dry matter, and the composition and the rate and extent of degradation of individual feed fractions (the types of carbohydrates and protein) in dietary dry matter. Important fermentation conditions are rumen pH, the presence of unsaturated long chain fatty acids, the composition of the microbial population in the rumen, the dynamics of the passage of particles, fluid and microbial matter, the inflow of saliva and the absorption capacity of the rumen (Bannink, 2007). The combined effect of both dietary characteristics and ruminal fermentation conditions is represented in conditions that characterize the ruminant (Bannink, 2007), such as production level, stage of lactation, grazing regime, and feeding regime (diet supplementation, concentrate feeding, and protein sources).

It is complicated to use factors, such as mentioned above, to predict the course of ruminal fermentation, extend of organic matter digestion, methane yield and the productive response of ruminants because these factors are often interrelated (Smink *et al.*, 2003). The contribution of a single feed component or type of carbohydrate to methane yield is not necessarily consistent because of these interrelationships (Mills *et al.*, 2001). Some of the principle factors affecting rumen function and methane production are discussed below.

Level of feed intake

The relationship between methane emissions (g/d) and DM intake is positive (Shibatha and Terada, 2010). Blaxter and Clapperton (1965) demonstrated that on diets studied by the authors the absolute daily CH_4 production (g/d) increased with increases in intake, but at a declining rate. Johnson and Johnson (1995) stated that as the daily feed intake of any given animal increase, the percentage of dietary gross energy lost as methane decreases by an average of 1.6% per level of intake. The reduction in methane production with increasing level of intake is associated with a decreased rumen residence time and decreased ruminal fermentation (Hodson, 1997; Moss *et al.*, 2000; Vlaming,

2008). A rapid passage rate favours propionate production and the relevant hydrogen use (Moss *et al.*, 2000). The level of feed intake has a greater effect on methane production when diets of lower digestibility are fed to animals. Molano and Clark (2008) and Beauchemin and McGinn (2006) found that when fresh forage or silage and concentrate mixtures were fed to animals that the level of feed intake had no effect on methane yield. These results supported data from Johnson and Johnson (1995) who found that at high intakes of highly digestible diets, low fractional methane losses occur. The major effect of feeding level is explained by its consequences on passage of feed particles out of the rumen (Moss *et al.*, 2000).

Diet composition

Diet has an important impact not only on methanogen numbers but also on methane production, as both the quantity and quality of feed can alter the ruminal fermentation pattern (Kumar *et al.*, 2009). The major constituents of the diet – sugars, starch, fibre, protein, and lipid – appear to have varying impacts on methane emissions (O'Hara *et al.*, 2003). Kirchgesner *et al*. (1995) illustrated that on average crude fibre provides about 60%, nitrogen free extract 30%, crude protein 10% and ether extract a minor proportion of total methane production. However, O'Hara *et al*. (2003) stated that variations within and between the major classes of nutrients can cause major shifts in methane production.

Ruminal volatile fatty acid ratios and concentrations as well as methane production vary with different carbohydrates fermented (Bannink, 2007; Kumar *et al.*, 2009). Simple carbohydrates produce more methane (0.45 moles/mole of hexose) as compared to complex carbohydrates (0.3 moles/mole of hexose). The type of carbohydrate fermented influences methane production most likely through impacts on ruminal pH and the ruminal microbial population (Johnson and Johnson, 1995). Fermentation of cell wall fibre yields higher acetic: propionic acid ratio and higher methane losses (Moss *et al.*, 2000). Moe and Tyrrel (1979) found that the fermentation of soluble carbohydrates is less methanogenic than cell wall carbohydrates (cellulose and hemicellulose) and Johnson and Johnson (1995) suggested that non-cell wall components should be further separated into soluble sugars and starch. Soluble sugars are more methanogenic than starch (Hinderichsen *et al.*, 2005). As the starch content in the diet increases rumen pH decreases, making the ruminal environment more hostile for methanogens to survive (O'Hara *et al.*, 2003).

Moss *et al*. (2000) stated that the concentrate to forage ratio of a diet may have an impact on rumen fermentation, with a higher grain proportion in the diet resulting in a decline in the acetate to propionate ratio and lower methane production. Gross energy intake lost as methane is typically 6-12% on forage based diets, while diets containing a high percentage of concentrates (>90% grain) results in methane production of 2-3% of gross energy intake (Johnson and Johnson, 1995). Feeding of a high concentrate: low roughage diet produces less methane as compared to a low concentrate: high roughage diet (Kumar *et al.*, 2009). Van Soest (1982) indicated that a high grain diet and/or the addition of soluble carbohydrates results in an increased ruminal passage rate, lowered ruminal pH, as well as increased propionate production. These factors may combine to make the ruminal environment less suitable for methanogens. Sigh and Sigh (1997) reported a decrease in the numbers of methanogens and cellulolytic bacteria when a concentrate: roughage ratio of 75: 25 was fed to cattle. Moss *et al*. (2000) estimated that increasing the level of dietary non-structural carbohydrate by 25% would result in a reduction in methane of approximately 20%. Lower levels of carbohydrate supplementation do not seem to give the same pro rata reductions in methane production (Boadi *et al.*, 2002).

Pelchen and Peters (1998) analysed datasets from literature where sheep was fed in calorimeters and developed regression equations to predict methane emissions. When these authors included crude protein as an independent variable it had a negative sign, indicating a negative relationship between dietary protein and expected methane emissions. Yan *et al*. (2006) also reported a decrease in methane production with an increase in dietary crude protein ($R^2 = 0.54$).

The addition of lipids to a diet can suppress methane production. Johnson and Johnson (2002) reported that three factors – the quantity, the degree of saturation and the chain length of lipids could influence enteric methane production. The decrease in methane production when lipids are added to a diet could be attributed to the biohydrogenation of poly-unsaturated fatty acids providing an alternative hydrogen acceptor to the reduction of CO_2 instead of CH_4 as well as the suppression of fermentability of feeds and therefore reducing CH_4 production (Johnson and Johnson, 1995).

Digestibility

Methane emissions are closely related to the amount of rumen fermented OM or the amount of digestible OM (Moss *et al.*, 2000). When comparing two feedlot diets Beauchemin and McGinn (2006) reported increased methane emission from animals receiving a diet with lower DM, OM, GE, NDF and CP digestibilities. Improving the availability and digestibility of pasture increases the enteric methane emission (g/day) produced by ruminants, but it reduces the methane yield per unit of product produced (Alcock and Hegarty, 2006). Pelchen and Peters (1998) reported that an increasing intake of digestible energy, crude fibre and nitrogen-free extract also increased the amount of CH_4 emitted by sheep. These authors also found that an increasing intake of crude protein and a higher energy density of the diet decreased the methane emissions. Increasing digestibilities of rations increase methane emissions, but Pelchen and Peters (1998) reported that at digestibilities above 72% the increasing effect on methane emissions faded out. Increased digestibilities of diets mean less methane emissions per unit of production. As the digestibility of a feed increases, the amount of energy available to the animal also increases, and therefore the amount of methane emitted per kg of product decreases (Plechen and Peters, 1998).

The relationship between enteric methane emissions and feed digestibility is also very dependent on the level of intake. Blaxter and Clapperton (1965) found that when feed is offered at low levels of intake, methane emissions (MJ/100MJ) increases as digestibility increases, whereas with high intakes methane emissions fall as digestibility increases. Similar results were published by Hart *et al*. (2009) who found that at high feed intake levels, the proportion of energy lost as CH_4 decreased as the digestibility of the diet increased.

Roughage Utilization

Forage species

Pasture species may play a significant role in enteric methane emissions. Legumes often give rise to increased feed intakes and have higher digestibilities compared to grass. Mizaei-Aghsaghali *et al*. (2015) calculated the methane emissions of grass and legume hay and found higher rates of emissions for grass hay compared to the legume hay. McCaughey *et al*. (1999) found similar results when these authors examined the methane emissions from cows grazing a lucerne-grass mixture (78% lucerne and 22% meadow brome grass) or a 100% meadow brome grass pasture. These authors found that although the cows grazing the lucerne-grass mixture had significantly higher dry matter intakes (11.4 ± 0.4 vs. 9.7 ± 0.4 kg DM/d) they produced less methane (373.8 ± 10.1 vs. 411.0 ± 10.1 L CH_4 /d)

compared to the cows grazing the grass only pasture. This reduction in the CH_4 emissions could be attributed to a reduction in the proportion of structural carbohydrates in the lucerne-grass pasture. The NDF of the lucerne based pasture (58.4 ± 0.8%) was lower than that of the grass based pasture (73.1 ± 0.8%). Santoso *et al*. (2007) found similar results and stated that the methane release by sheep increased with increasing NDF digested. Minson and Wilson (1994) stated that the inclusion of legume-based forages in a diet is associated with higher digestibilities and faster passage rates resulting in a shift toward high propionate production in the rumen and reduced methane production.

Margan *et al*. (1988) found that sheep fed tropical grasses had higher methane yields (as a percentage of gross energy intake) of 7.4% compared to sheep fed temperate forages (6.0%). McCrabb and Hunter (1999) found similar results but with higher methane emissions for tropical grasses (10.4 and 11.4%). Ulyatt *et al*. (2002) stated that it would be expected that methane emissions from C4 grasses would be higher than emissions from C3 grasses at the same level of intake as tropical C4 grasses generally have higher cell wall carbohydrate concentrations and lower DM digestibilities than temperate C3 grasses at the same stage of growth (Minson, 1981). Earlier, Blaxter and Wainman (1964) and Moe and Tyrell (1979) showed that as the proportion of cell wall carbohydrate increases in the diet of cattle and sheep at high levels of intake, their methane emissions also increased. BassiriRad *et al*. (1998) reported that C4 species has an advantage over C3 species at elevated CO_2 concentrations through the enhanced ability of perennial C4 species to increase their uptake of NO_3^- and PO_4^{3-} to considerably more than the perennial C3 species. Knapp *et al*. (1993) reported increased photosynthetic capacity for the C4 grass *Andropogon gerardii* under conditions of elevated CO_2 and water stress. Pospisilova and Carsky (1999) noted that the "antitranspirant effect" of atmospheric CO_2 enrichment is often more strongly expressed in C4 plants than in C3 plants. Ward *et al*. (1999) stated that C4 species would be more competitive than C3 species in regions receiving more frequent and severe droughts, like South Africa.

Cultivar selection could play a role in enteric methane production from pastoral production systems. Lovett *et al*. (2006) stated that the amount of substrate required to produce 1 ml of CH_4 differed significantly ($p<0.01$) between *Lolium perenne* cultivars. Differences in the methane emissions have also been shown by Wang *et al*. (1997) using three rice cultivars. The results of Lovett *et al*. (2006) suggest that differences exist between cultivars in the manner in which OM is partitioned following microbial fermentation and this could affect methane production. These differences could be exploited through cultivar selection and plant breeding programmes to reduce enteric methane emissions from pastoral production systems.

Animal variation

Variations in enteric methane production within an individual animal, between animals and between breeds have been reported by several researchers. Blaxter and Clapperton (1965) reported a 7% within-animal variation in absolute CH_4 production from day-to-day in sheep and cattle when the animals were fed a constant amount of consistent quality feed. Boadi and Wittenberg (2002) found a 27% coefficient of variance for day-to-day CH_4 production under *ad libitum* or restricted diet conditions. In a trial by Grainger *et al*. (2007) when the authors accounted for differences in intake they reported a 6% coefficient of variation in daily CH_4 production.

Differences between animals have also been reported (Blaxter and Clapperton, 1965; Johnson *et al.*, 1994; Lassey *et al.*, 1997; Boadi *et al.*, 2002; Pedreira *et al.*, 2009). Grainger *et al*. (2007) reported a 17.8% variation in daily CH_4 production between lactating dairy cattle fed *ad libitum*. Variations in methane emissions among genetic groups were also shown by Pedeira *et al*. (2009). These authors

found that lactating cows produced more methane (353.8 g/day) than dry cows (268.8g/day) and heifers (222.6 g/day) and that Holstein cows produced more methane (299.3 g/day) than Crossbred cows (264.2 g/day). The Holstein cows, with a higher milk production potential, however produced less CH_4 ($p<0.05$) per unit of dry matter intake (19.1g/ kg) than the Crossbred cows (22.0 g/ kg). These differences could be attributed to differences in animal body size and the organic matter intake potential, since there is a direct relation between methane production and digestible organic matter intake (Pedeira *et al.,* 2009). Boadi and Wittenberg (2002) suggested that the variation in daily CH_4 production could be attributed to digestive tract characteristics. This variation in digestive parameters could be influenced by a number of variables including type of feed, level and frequency of feeding, rate of intake, saliva production and composition, rumen pH, rumen capacity, and retention time of fluid and particulate matter in the rumen (Margan *et al.,* 1982; Pinares-Patino *et al.,* 2003; Hegarty, 2004; Pedreira *et al.,* 2009). These digestive and feeding parameter variables could influence the microbial balance in the rumen and thus affect CH_4 production (Vlaming, 2008).

Methane from excreta

A relative small amount of methane is produced in the large intestine of ruminants. It is therefore possible that microbes, including methanogens, would be present in voided faecal matter and could continue the fermentation processes under favourable conditions. Several researchers quantified the methane release from faecal matter under grazing conditions and reported values ranging from 0.2% to less than 3% of that produced in the rumen. Lodman *et al*. (1993) stated that only the storage of faecal material in anaerobic lagoons is likely to produce significant methane emissions from livestock manure.

Measuring methane emissions from livestock.

Accurate measurements of CH_4 emissions from livestock are required for establishing national inventories, assessment of mitigation strategies, development of quantification protocols as well as for genetic selection. Several methods have been used to measure methane emissions from livestock. These range from building elaborate chambers with various gas analysers to tracer techniques, mass-balance techniques, and the use of lasers. Selection of a technique is dependent on the research question asked as each technique has its strengths and weaknesses (Johnson and Johnson, 1995).

Individual animal techniques

Respiration chambers

Respiration chambers or calorimeters have been used to collect and analyse methane emissions from animals (Kebreab *et al.,* 2006; Hammond *et al.,* 2016). This technique involves measurement of the volume of gases entering and exiting the chamber. Chambers are typically constructed of steel and plexiglass with an air conditioning system to provide environmental control within a temperature range of 18 ±2°C and relative humidity of 60 ± 10%. Gaseous composition of the ingoing and outgoing air from the chamber can then be measured and analysed using various methods (Kebreab *et al*., 2006). Closed circuit calorimetry provides the most accurate measure of total methane emitted over an experimental period of approximately 3 days (Vlaming, 2008) including methane from ruminal and hindgut fermentation (Johnson and Johnson, 1995). Despite the accuracy of measurement, the expense of construction and operation (Kebreab *et al.,* 2006), the labour

intensiveness with the daily removal of faecal and urinary matter, and the inapplicability to animals under grazing conditions (O'Hara *et al.*, 2003) limit the use of this method.

Recently, many respiration measurements undertaken with ruminants have been done using open circuit chambers (O'Hara *et al.*, 2003; Hammond *et al.*, 2016). This system involves the passing of outside air through a chamber housing an animal. Air flow and concentrations of O_2, CO_2 and CH_4 are measured in the air entering and leaving the chamber. Methane production is calculated using the air flow in the chamber and the difference in CH_4 concentrations entering and exiting the chamber.

Gardiner *et al*. (2015) discussed three critical sources of variation for CH_4 measurement through respirations chambers. These sources of variation were analyser error, ducting efficiency, and the mixing of air within the chamber. Of these, ducting efficiency from chambers to analysers and air flow measurements was the largest source of variation between chamber measurements.

There are a few variations of the open circuit calorimeters. A ventilated hood system is based on the same principles as discussed above but only part of the animal in enclosed. McLean and Tobin (1987) described the design and operation of the hood system. This technique involves the use of an air tight box or hood that surrounds the animals head with a flexible seal around the animal's neck (Takahashi *et al.*, 1999). Boadi *et al*. (2002) used a ventilated hood system that allowed a stall tied animal freedom to stand or lie down, as well as free access to feed and water. Gas analyses are conducted in a similar way as with other calorimeters. Animals need to become accustomed to the hood apparatus, and require extensive training, which limits the use of ventilated hoods for screening large numbers of animals (Hammond *et al.*, 2016).

Face masks may also be used to quantify methane production (Johnson and Johnson, 1995). The method works on the same principles as that of the open-circuit calorimeter and it is a variation of the hood system. The system works by fitting a mask over the animal's head for a limited period, one hour measurements several times per day, instead of using a hood (Kempton *et al.*, 1976; Vlaming, 2008). Animals cannot eat or drink during the measurement periods and gas analyses are done in the same way as for the open-circuit calorimeters. Johnson and Johnson (1995) reported that using face masks could give quite variable results because of the normal daily variations in methane emissions. The face mask technique could underestimate methane production by as much as 9% (Liang *et al.*, 1989). Goopy *et al*. (2015) reported on the use of portable accumulation chambers (PAC) to measure methane emissions from individual animals over a 1 or 2 hour period. The PAC technique provides a single spot sample of accumulated gasses emitted by an animal.

Tracer techniques

These techniques are useful because they do not require specialised chambers for animals, as animals can be measured in standard animal stalls or crates or measured in the field (Vlaming, 2008). Tracer techniques use inert gasses that are infused into the rumen where they are not metabolized by the animal and where they have no effect on rumen fermentation patterns. Boadi *et al*. (2002) mentioned that as tracer techniques estimate, rather than measure methane emissions, they do not tend to be as accurate as calorimetry measurements. These techniques require the use of large numbers of animals and greater replication per experiment to improve accuracy.

Johnson *et al*. (1994) described the sulphur hexafluoride (SF_6) technique developed by Zimmerman (1993) which is the most common tracer technique at present. The technique assumes that the rate of SF_6 emission is the same as that of CH_4 emissions. This technique involves the placing of a

permeation tube containing SF_6 in the rumen, collecting samples from the animal's nose and mouth and determining CH_4 and SF_6 concentrations by gas chromatography. These concentrations are used to calculate methane production from the ratio of CH_4 and SF_6 concentration multiplied by release rate of SF_6 from the permeation tube. Hammond *et al*. (2016) reported that the SF_6 technique yielded mean CH_4 emissions that vary from 5 to 10% from emissions measured by respiration chambers using the same animals.

Moate *et al*. (1997) described a tracer technique using ethane (C_2H_6) to measure rumen gas kinetics. These authors continuously injected ethane into the rumen and simultaneously collected rumen gas, which was analysed for C_2H_6, CH_4, H_2, CO_2, hydrogen sulphide (H_2S), and O_2 to study gas kinetics in the rumen. Total methane production can be calculated by dividing the proportion of methane by the proportion of ethane in the collected gas and multiplying the fraction by total ethane infused into the rumen (Kebreab *et al.,* 2006). This technique does not account for gas dissolved in ruminal fluid or trapped in gas bubbles. Vlaming, (2008) stated that as the tracer needs to be infused directly into the rumen that this method is not suitable to measure methane production from grazing or large groups of animals.

Isotope dilution techniques

Isotopic techniques used for measuring enteric methane production require the use of radioactively labelled CH_4. Murray *et al*. (1976) used a technique where radioactively labelled CH_4 is continuously infused into the rumen at a known rate or dose to achieve mixing with CH_4 in solution in the rumen fluid. After equilibrium is reached, the specific activity of CH_4 in the gas phase, which is directly derived from the pool in solution, indicates the rate of ruminal production of CH_4 (Murray *et al.,* 1976; Kebreab *et al.,* 2006). Animals must be rumen cannulated to allow re-entry into the rumen for infusing the labelled CH_4 and for gas sample collection and expensive analytical equipment is required to measure the specific activity of the labelled isotope. Johnson and Johnson (1995) also named the difficulty in preparation of the infusion solution due to low solubility of CH_4 gas as a major limitation of this technique.

Automated head chambers (Greenfeed)

The Greenfeed system (C-Lock Inc., South Dakota, USA) is a static short-term measurement device that measures CH_4 emissions from individual animals by integrating measurements of airflow, gas concentration, and detection of head position during each animal's visit to the unit (Zimmerman and Zimmerman, 2012; Hammond *et al.,* 2016). The system can be used in a variety of environments, including under grazing conditions. Hristov *et al*. (2015) gave a detailed explanation of the measuring technique employed by the Greenfeed system.

Handheld laser methane detector

Chagunda *et al*. (2009) examined the ability of a handheld laser methane detector (LMD) to estimate enteric methane output in dairy cows without any disturbance to the normal activity of the animals. The LMD is a handheld gas detector for remote measurements of column density for methane concentration. This system is based on infrared absorption spectroscopy, using a semiconductor laser as a collimated excitation source and employing the second harmonic detection of wavelength modulation spectroscopy to establish a methane concentration measurement. Daily methane production data reported by the authors were numerically comparable to the range reported in literature (Holter and Young, 1992; Vermorel, 1995; Griffith *et al.,* 2008). On average the enteric

methane estimates were higher than those empirically estimated (356.8g/ d vs. 304.5 g/ d). The authors suggested that the differences could be due to the assumptions used in the calculation of daily methane production. Limitations to the LMD technique are the ambient conditions at time of sampling. Wind speed, temperature, humidity, and atmospheric pressure will influence the accuracy of measurements and needs to be considered (Chagunda, 2013).

Group techniques

Group techniques have the advantage that they are less intrusive than either tracer or enclosed techniques. The major disadvantage of group techniques is that they do not measure methane production from individual animals. O'Hara *et al.,* (2003) suggested that the lack of accuracy of group techniques means that these techniques are not suitable to detect small differences between groups or treatments.

Polythene tunnel

The system is constructed using a large polythene tunnel with two small wind-tunnels used to blow air into, and draw air from the larger tunnel. Murray *et al*. (1999) described the construction and operation of the system in detail. Concentration of methane in air entering and leaving the tunnel is measured, Lockyer and Jarvis (1995) described the use of a gas chromatograph fitted with a flame ionization detector to measure methane concentrations in air samples. The polythene tunnel is kept at a slight negative pressure, so that any leaks in the tunnel results in background air entering the tunnel. The advantage of the system is that it allows free movement of animals inside the tunnel and that it is inexpensive to build (Kebreab *et al.,* 2006). Animals are also allowed a certain degree of selection within the confines of the tunnel. Problems associated with polythene tunnels are the control of temperature inside the tunnel during high ambient temperatures as is found in tropical regions. Lockeyer and Jarvis (1995) reported that daily estimates of methane emissions using polythene tunnels appear to be lower than other estimates. Murray *et al*. (1999) also reported higher methane production from sheep fed roughage diets form open circuit respiration chambers compared to tunnels (31.7 ± 0.35 vs. 26.9 ± 0.46 L/ kg DM intake respectively). The authors suggested that the differences in animals' behaviour between the two systems could account for the differences in methane production.

Micrometeorological mass balance technique

Harper *et al*. (1999) developed a micrometeorological mass difference technique to measure CH_4 production by cattle under pasture and feedlot conditions. This method requires sophisticated equipment and qualified personnel with expert knowledge in air movement. The technique is based on the calculation of CH_4 budgets for an area in which animals were feeding from measurements of wind speed and atmospheric CH_4 concentrations on the upwind and downwind boundaries (Kebreab *et al.,* 2006). The micrometeorological mass balance technique can also be used to quantify gasses from manure. One of the limitations of the method is that the measurements are influenced by light winds and rapid changes in wind direction (Harper *et al.,* 1999).

***In Vitro* methods**

In vitro cultures allow the determination of methane production when different diets are fermented alone or in the presence of additives to study their effects on rumen fermentation (Moss, 1994; Cattani

et al., 2014). There are two main *in vitro* methods used to measure methane production from ruminal fermentation using ruminal fluid: i) batch cultures in sealed serum bottles (Moss *et al*., 1994) and ii) the fermenter called Rumen Simulation Technique (RUSITEC) that is a semi-continuous culture (Czerkawski and Breckenridge, 1977).

The Hohenheim gas test (HGT) apparatus estimates the digestibility and the metabolizable energy content of ruminant feedstuffs. This system was developed by Menke *et al*. (1979) and Menke and Steingass (1988) described the operation of the HGT in detail. However, there are a few modifications necessary to enable the system to analyse for the composition of ruminal fermentation gasses (Soliva *et al.,* 2003). This system utilizes an incubator and modified HGT glass syringes with a gas chromatograph using two detectors, a thermal conductivity, and a flame ionization detector, for the analyses of fermentation gas composition (Soliva and Hess, 2007).

The rumen simulation technique (RUSITEC) was developed by Czerkawski and Breckenridge (1977) to maintain a normal ruminal microbial community under strictly controlled conditions over an extended period. In this system feed samples are placed in perforated nylon bags with a 100 µm pore size in rumen fluid filled fermenters. During incubation gas volume is measured using a gas flow meter as described by Lopez and Newbold (2007). Gas samples are taken using gas tight syringes and analysed using a gas chromatograph using the same two detectors as with the Hohenheim gas test (Lopez and Newbold, 2007; Soliva and Hess, 2007).

Comparison of measuring techniques

Various techniques and equipment are used to measure methane production from ruminants as described above. Johnson *et al*. (1994) and Boadi *et al*. (2002) compared the methane production using the SF_6 tracer technique and respiration chambers and found no significant differences. These authors also did not detect any day to day variation of CH_4 production between the two methods but they did report significant between animal differences. Hammond *et al*. (2016) reported a 5 to 10% variation between emission results obtained through the SF_6 technique compared to respiration chambers.

Murray *et al*. (1976) compared methane estimates using the mask technique and the isotope dilution technique and found no significant differences between the two techniques. When comparing the polythene tunnel and respiration chamber techniques, Murray *et al*. (1999) found that methane production measured using the respiration chamber was 12.9% greater than that in the tunnel. These authors suggested that the differences could be due to housing effects during sample collection.

In a comparison of methane emissions from sheep measured by the micrometeorological mass balance technique and the SF_6 technique, Leuning *et al.* (1999) showed that on average the values were very similar (11.9 ± 1.5 vs. 11.7 ± 0.4 g/d respectively). The micrometeorological mass balance technique tended to show some between animal variations on a daily basis. There is a need to standardize operating procedures of techniques and to develop guidelines for conducting and assessing data from *in vivo* studies designed to measure enteric CH_4 emissions by ruminants (Hammond *et al.,* 2016). This will allow the evaluation and comparison of nutritional strategies to reduce methane and the development of methane emissions factors (Kebreab *et al.,* 2006) which can be used as a platform to develop prediction models.

Prediction equations and Models

Equations and models to predict methane production from ruminants were developed since the quantification of methane produced by ruminants is time consuming and requires complicated and often expensive equipment and specialized skills. Several models that predicts enteric methane production have been published (Kriss, 1930; Bratzler and Forbed, 1940; Axelsson, 1949; Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979; Holter and Young, 1992; Krichgessner *et al.*, 1994; Krichgessner *et al.*, 1995; Lescoat and Sauvant, 1995; Pitt *et al.*, 1996; Johnson and Ward, 1996; Kohn and Boston, 2000; Yan *et al.*, 2000; Mills *et al.*, 2001; Mills *et al.*, 2003; Hindrichsen *et al.*, 2004; Van Laar and Van Straalen, 2004; Schils *et al.*, 2006; Dijkstra *et al.*, 2006; Offner and Sauvant, 2006; Danfaer *et al.*, 2006; Huhtanen *et al.*, 2015). These models vary in complexity and range from simple static, empirical models to complicated dynamic, mechanistic models (Bannink, 2007). The accuracy of the earlier models was questioned by Johnson and Johnson (1995). These authors concluded that simple empirical equations based on feed characteristics cannot be expected to predict methane accurately under various production conditions.

Bannink (2007) stated that for a model to predict methane production under various production conditions more accurately than empirical equations it should include the degradation of organic matter, efficiency of microbial growth and the type of volatile fatty acid produced. Baldwin *et al.* (1987), Dijkstra *et al.* (1992), Mills *et al.* (2001), and Kebreab *et al.* (2004) produced more detailed models capable of representing substrate degradation as a function of the effective concentrations of substrate as well as of degrading classes of ruminal micro-organisms. These models consider the interactions between feedstuffs that govern nutrient degradation, including the effect of rapidly degradable carbohydrates on fibre degradation.

Thornley and France (2007) mentioned that empirical models can only be applied within the range of data used in their development and as such is unsuitable to evaluate new feeds or feeding strategies. Mechanistic models are the preferred choice to identify possible mitigation options (Van Laar and Van Straalen, 2004).

The production of VFA in the rumen has a major effect on the amount of CH_4 produced. Dijkstra *et al.* (2007) stated that the quantification of the type of VFA produced is an important element that should be included in any mechanistic model to explain CH_4 production. Empirical models do not include variations in VFA profiles that might result from different ruminal fermentation conditions (Bannink, 2007). Kohn and Boston (2000) reported that with an increased rate of substrate fermentation and a higher partial gas pressure of H_2 in the rumen, the efficiency of CH_4 production declines as well as that of acetate formation, and as a result propionate formation becomes relatively more favourable. Such conditions are strongly correlated to high rates of fermentation and more acidic conditions in the rumen (Bannink *et al.*, 2006). Benchaar *et al.* (1998) and Kebreab *et al.* (2006) compared empirical and mechanistic models and found that dynamic mechanistic models always performed among the best. Mechanistic models are better capable to evaluate the consequences on details of rumen function, interactions among feed components, and other aspects such as diet digestibility, milk yield, excretion, manure composition and ammonia emissions (Bannink, 2007).

Mitigation Options

Agriculture, excluding forestry and land use, is the second highest contributor to South Africa's greenhouse gas emissions, and it is the highest methane emission producing sector. Livestock accounts for 90% of agricultural CH_4 emissions as mentioned earlier. Reducing the CH_4 emissions from livestock could significantly decrease total livestock greenhouse gas output from South Africa.

Current enteric methane mitigation practices either target reductions of methane emissions directly or aim to improve animal productivity. The mitigation potential of any of the available options discussed below will vary depending on the type of livestock production system employed. It is easier to manipulate the diet of animals and administer additives daily in intensive production systems compared to extensive pasture based production systems. The improvement of animal productivity through selection and breeding requires investments in education and guidance to farmers to implement efficient selection programs.

Hristov *et al*. (2013) and Mirzaei-Aghsaghali *et al*. (2015) evaluated several greenhouse gas mitigation practices in livestock systems and these authors showed that mitigation practices vary among locations and conditions. Livestock in developing countries are mainly in extensive production systems and used for many purposes other than food production – as symbols of social status, for their religious values, for draft activities, for the energy of their manure, and as alternative sources of income. In order for a mitigation strategy to be sustainable and effective it should consider all aspects of a specific production system. This illustrates the importance of developing country specific mitigation strategies.

Nutritional and management strategies

Type and proportion of concentrate in the diet

The nature and rate of carbohydrate fermentation influences the proportion of individual volatile fatty acids produced in the rumen (Boadi *et al.*, 2004) and the amount of excess hydrogen available in the rumen which can be converted to methane (Afshar *et al.*, 2008). Moe and Tyrrell (1979) compared the effect of structural vs. non-structural carbohydrates on methanogenesis and found that fibre fermentation increases methane production compared to soluble carbohydrate fermentation. These authors also reported that the production of methane per gram of cellulose digested is nearly three times that per gram of hemicellulose digested and five times that per gram of soluble residue digested. The formation of acetic acid is accompanied by the production of hydrogen, whereas the formation of propionic acid involves a net uptake of hydrogen. Propionic acid formation competes directly with ruminal methane formation. Orskov (1986) reported that the ratio of acetic: propionic acid in the rumen tends to increase as the fibre content of diets increase and the author found a negative relationship between the proportion of acetic acid in rumen fluid and the efficiency of utilization of metabolizable energy.

Diets rich in starch favours propionate-forming microbes and therefore divert H_2 away from methanogens (Janssen, 2010). Hindrichsen *et al.* (2004) stated that sugars tend to promote butyrate formation, at the expense of propionate, which provide H_2 for methanogens and therefore increases methane production. Johnson and Johnson (1995) stated that a roughage based diet will favour acetic acid production and increase methane production per unit of fermentable organic matter in the rumen. Structural carbohydrate fermentation results in a greater loss of gross energy intake as methane than

the fermentation of sugars and starches (Boadi *et al.*, 2004). This is due to a decreased rate of ruminal fermentation and a decreased rate of passage out of the rumen, which favours a higher acetic: propionic acid ratio (Hegarty and Gerdes, 1998). Monteny *et al*. (2006) reported a 14.7% reduction in total methane production when replacing sugars with starch in a diet.

A high rate of fermentation of organic matter in the rumen is known to affect the type of VFA produced (Monteny *et al.*, 2006). When VFA production rates increase and rumen pH drops, a shift occurs towards more propionate production. This is mainly due to shifts in the abundance of rumen micro-organisms. Propionate serves as an alternative hydrogen sink to methane (Orskov, 1986; Hergarty, 1999). High rates of fermentation of grains will lower ruminal pH, which inhibits the growth of protozoa and methanogens (Hegarty, 1999). Russel (1998) found that the rumen fluid of cows fed a 90% concentrate diet had lower rumen pH values (6.22 vs. 6.86), higher volatile fatty acid concentrations (85 vs. 68 mM) and lower acetate: propionate ratios (2.24 vs. 4.12) than the rumen fluid of cows fed a 100% forage diet.

Variations within a certain type of carbohydrate have been mentioned in the literature. Ovenell-Roy *et al*. (1998) reported differences in the methane production from four cultivars of barley fed to lambs. These differences could be exploited in plant breeding programs to further reduce the methane production potential of carbohydrates.

Forage quality and digestibility

Increased digestibility of pasture for grazing ruminants is one of the most practical methods to reduce enteric methane emissions (Hegarty, 1999; Iqbal *et al.*, 2008; Hristov *et al*., 2013). However, the improvement of forage digestibility will have a greater impact on enteric methane production in developing countries or when tropical, C4 grasses are concerned. Veen (2000) stated that in countries where the digestibility of the basal diet is already high, such as in the Netherlands, the improvement of digestibility will have limited potential as a mitigation strategy. Quality of forages depends predominantly on maturity and less mature forage often has a higher N concentration and a lower NDF and sugar concentration (Bannink, 2007). Hristov *et al*. (2013) reported that pasture quality has a significant impact on enteric methane emissions when researchers studied the methane emission from grazing animals throughout the grazing season. Boadi and Wittenberg (2002) demonstrated that steers grazing pastures during the early part of the grazing season had 44% and 29% less energy lost as methane ($p<0.01$) than steers during the mid and late grazing periods respectively. Steers also experienced a 54% reduction ($p<0.01$) in enteric methane emissions upon entry vs. exit of a paddock. Methane emissions appear to be influenced by pasture dry matter availability as well as quality. Boadi and Wittenberg (2002) concluded that enteric methane emissions are highest when an animal is presented with poor quality forage and has limited opportunity to select higher quality forage as a consequence of reduced dry matter availability.

Forage species

Archimede *et al.* (2011) conducted a meta-analysis investigating differences in CH_4 emissions from ruminants fed C3 vs. C4 grasses and sub-tropical and temperate legumes. These authors concluded that ruminants fed C4 grasses produced 17% more CH_4 (per kg OM intake) compared to animals fed C3 grasses and 20% more CH_4 than animals fed sub-tropical legumes. McCaughey *et al*. (1999) observed significant higher DM intakes and lower methane production from animals grazing a lucerne-grass mixture compared to a 100% grass sward. Legumes generally have higher intakes and

digestibility than grass swards and thus give rise to higher digestibility (O'Mara, 2004). Minson and Wilson (1994) stated that the inclusion of legumes in a pasture or a diet is associated with higher digestibility, lower proportion of structural carbohydrates and a faster rate of passage resulting in a shift toward high propionate production in the rumen and reduced methane production.

Differences in the NDF concentration in forages and the greater methanogenic potential of structural vs. non-structural carbohydrates give rise to differences in methane productivity from different forages (O'Mara *et al.*, 2004; Hristov *et al*., 2013). As discussed earlier, C4 grasses may yield more methane per unit of intake than C3 grasses (Ulyatt *et al.*, 2002).

Cultivar selection could also play an important role in methane mitigation strategies (Iqbal *et al.*, 2008). Differences between cultivars were discussed earlier and Lovett *et al*. (2003) reported differences between two perennial ryegrass cultivars (Kells and Yatsan 1) in terms of methanogenic potential. These authors related these differences to the chemical composition of the cultivars but differences could also have been due to concentrations of organic acids. Iqbal *et al*. (2008) reported increased animal performance from perennial ryegrass cultivars containing high levels of water soluble carbohydrates. This shows that forage selection and breeding could play an important role in modern mitigation strategies.

Secondary plant compounds

Most plants synthesize secondary metabolites, which have different ecological or defensive functions (Harborne, 1999). Secondary metabolites do not represent a supply of nutrients to the animal but they may influence some of the animal's digestive and metabolic processes (Garcia-Gonzalez *et al.*, 2008). Garcia-Gonzalez *et al*. (2008) screened 158 plants, herbs, or spices to access their potential to reduce ruminal methane production. These authors identified three species *Rheum officinale*, *Frangula alnus* and *Allium sativum* which induced a noticeable reduction in methane production. Other researchers also observed reduced ruminal methane production with secondary compounds from some medicinal plants such as horsetail, sage (Broudiscou *et al.*, 2000), *Sesbania sesban*, *Acacia angustissima* (Zeleke *et al.*, 2005), *Sapindus sp*., *Terminalia chebula*, *Populusntremuloides*, *Syzygium aromaticum*, *Psidium guayaba* (Kamra *et al.*, 2005) and with extracts of fennel, clove, and garlic (Patra *et al.*, 2005). Some of the secondary compounds responsible for this effect was identified as thymol, eugenol, carvacal (Chiquette and Benchaar, 2005), tannins (Hess *et al.*, 2005), tea saponins (Liu *et al.*, 2005) and anthraquinone derivatives (Garcia-Gonzalez *et al.*, 2008).

Tannins have potential to decrease CH_4 emissions by up to 20% (Staerfl *et al*. 2012). A meta-analysis of *in vivo* experiments with tannins by Jayanegara *et al*. (2012) reported a close relationship between the dietary tannin concentration and CH_4 production per unit of digestible OM. These authors reported a decreased feed intake and a decrease in the nutrient digestibility, particularly of CP, with increasing tannin concentrations in the diet of animals. It is important that the benefits of reduced CH_4 production do not overshadow the possible detrimental effects of tannins on digestion and production of animals (Grainger *et al*., 2009). The reduction of CH_4 through the inclusion of tannins in animal diets is associated with a direct toxic effect of tannins on methanogens (Grainger *et al.*, 2009). Other benefits of feeding condensed tannins to ruminants are described by Waghorn *et al*. (1998) and Jones *et al*. (1994).

Plant saponins can also potentially reduce ruminal methane production and Beauchemin *et al*. (2008) showed that some saponin sources are more effective than others in terms of methane suppression. *Medicago sativa* (3-5%), *Sapindus rarak*, *Sapindus mokorossi*, *Yucca schidigera* (4%), *Quillaja*

saponaria (10%), *Acocia concinna* and *Emblica officinalis* are some of the plants or feed sources containing saponins reported by Kumar *et al*. (2008). Saponins cause a decrease in ruminal methane production from 20 – 60% on different substrates accompanied by a decrease in ammonia nitrogen and the numbers of ruminal protozoa (Kumar *et al.,* 2008). Hess *et al*. (2003) reported on the anti-protozoal effect of saponins and observed that defaunation enhanced propionate production with subsequent reductions in acetate and butyrate. Defaunation suppressed rumen methanogenesis by 43% over forage based diets when supplemented with tropical fruits (Hess *et al.,* 2008). Saponins reduce the protozoal population in the rumen which reduces the inter species hydrogen transfer to methanogenic bacteria attached to the protozoa (as discussed earlier) and thus reducing the amount of hydrogen available to methanogens to produce methane (Kumar *et al.,* 2008).

Plant derived essential oils that have anti-microbial properties have the potential to manipulate microbial activity in the rumen (Benchaar *et al.,* 2008). These authors observed *in vitro* effects of essential oils on ruminal nitrogen metabolism and reported that the effect was likely mediated by the impact of essential oils on hyper-ammonia producing bacteria resulting in reduced deamination of amino acids and production of ammonia nitrogen. The potential to select essential oils to reduce ruminal methane production is also mentioned by Benchaar *et al*. (2008) but these authors warned of a possible lack of long term applicability. The anti-microbial activity of essential oils could be due to interactions with the functions of bacterial cell walls, including electron transport, ion gradients, protein translocation, phosphorylation, and other enzyme dependent reactions (Dorman and Deans, 2000; Benchaar *et al.,* 2008). Evans and Martin (2000) observed that essential oil extracts from Thymus and Origanum showed strong methane inhibiting qualities *in vitro* but the acetate and propionate concentration was reduced. Extracts of garlic was found to be a highly suppressant of methane production *in vitro* and Kamra *et al*. (2005) reported a 64% reduction with no adverse effects on feed digestibility. Similar results were published by Busquet *et al*. (2005) who reported an increase in propionate and a decrease in acetate production *in vitro* when garlic oil (312 mg/L) was evaluated. These authors contributed the methane mitigation potential of these essential oils to a direct inhibition of rumen methanogens.

Dietary supplementation of dicarboxylic acids such as malate, fumarate, citrate, succinate, and aspartate reduces methane production (Martin, 1998; Callaway *et al.,* 1997; Bayaru *et al.,* 2001; Boadi *et al.,* 2004). Dicarboxylic acids are intermediates in the citric acid cycle and they serve as alternative electron sinks for H_2 (Boadi *et al.,* 2004; Iqbal *et al.,* 2008). Although cost limits their inclusion in dietary supplementation regimes, Muck *et al*. (1991) and Callaway *et al*. (1997) reported significant quantities of dicarboxylic acids in forages. These acids may constitute as much as 10% of the dry weight of pastures (Callaway *et al.,* 1997). Differences in dicarboxylic acid concentrations between forage species and within forage species have been reported (O'Mara, 2004). Callaway *et al*. (1997) reported that the malate concentration in plants decline with maturity and that legumes have higher concentrations of dicarboxylic acids than grasses. These authors also observed differences in the malate concentration between lucerne cultivars and between leaf and stem ratios. The development of forage species with high dicarboxylic acid concentrations through plant breeding programmes could play an important role in future methane mitigation strategies especially in regions that have a substantial grazing component in ruminant productions systems such as South Africa.

Forage management

Grazing management through the choice of grazing system and management of forage availability and quality could have a role to play in mitigation strategies (Mirzaei-Aghsaghali *et al*., 2015). DeRamus *et al*. (2003) found a 22% reduction in enteric methane emissions from cattle grazing high quality forage in an intensive production system (made possible through maintaining soil fertility). The reduction in methane emissions was related to better digestibility of high quality forage, which resulted in better efficiency of utilization. Similarly, Maas (1987) reported a decrease in the enteric methane production from animals offered fresh grass with increasing N concentrations. Pastures with a N concentration of below 3% yielded methane losses of around 6.5% of GEI, and pastures with a N concentration of 4.5% yielded methane losses of around 5.2% of GEI. High N concentration of pastures is associated with an increase in digestibility of energy (Bannink, 2007). Murray *et al*. (2001) observed that sheep grazing pastures that received 270 kg N/ ha produced significantly less methane than animals grazing pasture that received 70 kg N/ ha.

Proper grazing management to improve forage quality will increase animal intake and production and lower methane output per unit of product (Boadi *et al.*, 2004; Mirzaei-Aghsaghali *et al*., 2015). McCaughey *et al*. (1997) observed higher methane production for steers grazing continuously at low stocking rates (1.1 steer/ ha; 306.7 L/d) than for steers grazing continuously at high stocking rates (2.2 steer/ ha; 242.2 L/d). These authors also reported no effect of stocking rate on methane production if pastures are grazed rotationally. At low stocking rates (1.1 steer/ ha) methane production was 9% lower on rotational grazing than continuous grazing (McCaughey *et al.*, 1997).

Forage processing and preservation

A decrease in methane production as a consequence of ensilaging forages has been reported by Moss *et al*. (2000). Woodward *et al*. (2001) reported contradictory results and found very high methane losses when feeding ryegrass silage (10.8% of GE) and lotus silage (8.6% of GE). Grass silage is usually harvested at a later stage of maturity than fresh grass. This results in a lower DOM, a lower N concentration, and lower sugar concentrations. This might explain the results reported by Woodward *et al*. (2001). Benchaar *et al*. (2001) reported a 33% reduction in methane production when animals were offered lucerne silage instead of lucerne hay. O'Mara (2004) found that maize silage supported higher intakes and performance than grass silage and yielded less methane per unit product than grass silages. Boadi *et al*. (2004) stated that the addition of inoculant-enzymes during silage making seemed to hold a greater potential for reducing enteric methane emissions than other silage additives such as formic acid.

Grinding or pelleting of forages to improve the utilization by ruminants has been shown by Johnson *et al*. (1996) to decrease methane losses per unit of feed intake by 20 – 40% when fed at high intakes. Le-Liboux and Peyraud (1999) contributed the reduction in methane losses to lower fibre digestibility, decreased ruminally available organic matter and a faster rate of passage associated with ground or pelleted forages.

Manipulation of rumen fermentation

Alternative hydrogen sinks

This CH_4 mitigation strategy has recently received renewed attention (Hristov *et al*., 2013). Among these, fatty acids (Calsamiglia *et al.*, 2007; Kumar *et al*. 2009), fats and essential oils (Machmuller *et al.*, 1998; Fievez *et al.*, 2003; Iqbal *et al*. 2008), and dicarboxylic acids (Iqbal *et al.*, 2008; Hristov *et al*., 2013) have been evaluated the most as mentioned above. The effect of some of these mitigation agents are pH and diet dependent, and their use in methane reduction strategies may only be beneficial under specific conditions (Calsamiglia *et al.*, 2007).

Ionophores, probiotics and prebiotics

Ionophores alter the rumen environment through the modulation of movement of cations across cell membranes (Iqbal *et al.*, 2008). Monensin and lasolasid are two ionophores that have been used extensively in ruminant production systems. Iqbal *et al*. (2008) reviewed the effect of ionophores on methane production and reported four modes of action. Ionophores can reduce methane production by either (i) increasing feed conversion efficiency, (ii) selectively reducing acetate production through a shift in bacterial population from gram positive to gram negative organisms and prompting propionate formation (Moss *et al.*, 2000; Kumar *et al.*, 2009), (iii) inhibition of hydrogen release from formate, or (iv) depressing the protozoa population in the rumen or a combination of the above. Moss *et al*. (2000) also reported a reduction in DM intake and increased feed conversion efficiency when ionophores were included into ruminant diets. O'Kelly and Spiers (1992) attributed 55% of methane reduction to a reduced DM intake and 45% of the reduced methane production to specific ruminal activities. Iqbal *et al*. (2008) reported variations of between 0% and 76% in methane reduction when ionophores were included into ruminant diets. Omar (2004), Johnson *et al*. (1994) and McCaughey *et al*. (1997) reported a decrease in methane reducing potential of ionophores after a certain time period. Monensin lowered methane production by 25% in the short term but this decrease did not persist over the longer term (Van Nevel and Demeyer, 1995). This indicated the adaptation of ruminal microbes to ionophore inclusion into diets and may have an effect in limiting the use of ionophores as a long term sustainable methane mitigation strategy. Polyether ionophores such as salinomycin appears to have lasting methane reducing effects (Kumar *et al.*, 2009) but there are health concerns and risks that these ionophores could be absorbed from the rumen and end up in the meat or milk of treated animals.

Probiotics are microbial feed additives that influence ruminal fermentation directly resulting in increased animal productivity (Iqbal *et al.*, 2008). Yeast is the most widely used probiotic and mainly *Saccharomyces cerevisiae* and *Aspergillus orzae* (Moss *et al.*, 2000). Iqbal *et al*. (2008) reported that yeast cultures reduce methane production in four different ways: (i) through increasing propionate and butyrate production (Lila *et al.*, 2004); (ii) reducing protozoal numbers in the rumen (Newbold *et al.*, 1998); (iii) through the promotion of acetogenisis (Chaucherys *et al.*, 1995) and (iv) by improving animal productivity (Bruno *et al.*, 2005). The methane suppression qualities of probiotics are not consistent, Wallace and Newbold (1993) and Mwenya *et al*. (2004) reported a reduction in methane output per unit of product with the inclusion of probiotics in diets but in the same year McGinn *et al*. (2004) reported no significant methane reducing effects with the inclusion of probiotics in a diet. Kumar *et al*. (2008) stated that prebiotics such as galacto oligosaccharides, fructo oligosaccharides, mannan oligosaccharides and galactosyl lactose are non-digestible and aid in the proliferation of beneficial micro-organisms. These substances also act as propionate enhancers and thereby decrease methane production (Kumar *et al.*, 2008).

Salts

The alteration of the dietary cation-anion balance as a mitigation option has been investigated by Johnson *et al*. (1997). These authors used cannulated animals to add salts to the rumen to achieve dietary cation-anion balances of 10, 30, 50, and 70 meq/ 100g DM. The methane emissions were significantly lower in the diets containing 70 meq/ 100g DM compared to those receiving the 10 and 30 meq/ 100g DM diets. Johnson *et al*. (1997) also reported no adverse effects of the increase in dietary cation-anion balance on dry matter intake and ruminal fermentation characteristics. Calcium ions were also shown to have a tendency to reduce methane production when used as an additive in *in vitro* studies (Johnson *et al.*, 1997).

Halogenated methane analogues

Halogenated methane analogues can directly inhibit ruminal methane production (Hristov *et al*., 2013). Examples of such compounds are 2-bromoethanesulphonate, 3-bromopropanesulphonate, lumazine, propionic acid, ethyl 2-butynoate (Van Nevel and Demeyer, 1995; Kumar *et al.,* 2009). Chloral hydrate, which is converted to chloroform in the rumen, was also reported to reduce enteric methane production (Kumar *et al.*, 2009), but it can cause liver damage and death to sheep after prolonged feeding (Lanigan *et al.*, 1979). Amichloral appears to be a safer option and was reported to increase live weight gain in sheep (Kumar *et al.*, 2009).

Bromochloromethane inhibits enteric methane production by decreasing the number of methanogens by as much as 37% (Denman *et al.*, 2007). Earlier researchers reported the anti-methanogenic potential of bromochloromethane to diminish over time however, McCrabb *et al*. (1997) found that a combination of bromochloromethane and α-cyclodextrin was more stable and could reduce methane production over prolonged periods of time. Similar results were reported by Goel *et al*. (2009) who observed reduced methane emissions in batch and continuous fermentation by bromochloromethane.

2-Bromoethanesulphonate was shown to be a potent methane inhibitor as a bromide analogue of coenzyme M, involved in methyl transfer during methanogenesis (Kumar *et al.*, 2009). Van Nevel and Demeyer (1995) tested the use of 2-bromoethanesulphonate *in vivo* and found that it was only effective on the short term, the adaptation of methanogens partly explained this. Anderson *et al*. (2006) observed that the oral administration of both nitroethane and 2-nitropropanol resulted in reduced methane production and reported that nitroethane is the more effective methane inhibitor of the two. Reynolds *et al*. (2013) reported that 3-nitro-oxypropanol (3NP) decreased CH_4 production per unit of DMI in dairy cows. These authors, however, observed a sharp decrease in the CH_4 production immediately after 3NP administration and speculated that the compound may be rapidly absorbed, metabolized, or washed out of the rumen and that continuous infusion or feeding may be necessary if 3NP is to be considered as a viable mitigation measure.

Tezel *et al*. (2006) showed that quaternary ammonium compounds inhibit methanogenesis but these authors reported that the effects of these compounds diminished over long periods of incubation. As mentioned earlier, anthraquinone has also been shown to inhibit *in vitro* and *in vivo* methane production by inhibiting methyl-coenzyme M reductase (Garcia-Lopez *et al.*, 1996). Inhibitors of the enzyme hydroxymethylglutaryl-SCoA such as Lovastatin and Mevastatin has also been shown to reduce methane production by up to 50% through inhibiting the growth of *Methanobrevibacter* without any effects on the feed utilization efficiency as reported by Miller and Wolin (2001).

Acetogens

Acetogenic bacteria produce acetic acid by the reduction of carbon dioxide with hydrogen and reductive acetogenesis acts as an important hydrogen sink in hindgut fermentation (Moss *et al.*, 2000). Bacteria carrying out reductive acetogenesis have been isolated from the rumen (Greening and Leedle, 1989) but only in small numbers. Reductive acetogens are out competed in the rumen by ruminal methanogens and this limits their use to depress ruminal methane production as reported by Lopez *et al*. (1999). These authors suggested that reduction in ruminal methane production could be achieved through the use of acetogens as a daily feed additive.

Vaccines against methanogens

Australian scientists have produced and patented immunization procedures to reduce methane emissions. The vaccine was developed using an antigen derived from rumen methanogens (Baker, 1998) and an immunogenic preparation that reduces the activity of ruminal protozoa (Baker *et al.*, 1997). Baker (1998) stated that the vaccine reduced methane production in *in vitro* incubations, and that it significantly increased DM intake and wool growth when administered to animals *in vivo*.

Defaunating agents

Protozoa start to colonize the rumen environment approximately 3 weeks after birth (Iqbal *et al.*, 2008). The elimination of ruminal protozoa by any means is termed defaunation. Hegarty (1999) reviewed several defaunating techniques. These techniques included dietary manipulation (inclusion of fats and oils, saponin containing plants), the use of synthetic chemicals (copper sulphate, calcium peroxide, dioctylsodium sulfosuccinate and detergents), and natural compounds (vitamin A, non-protein amino acids and steroidal hormones). The symbiotic relationship between ruminal protozoa and methanogens accounts for approximately 40% of methanogenesis in rumen fluid. Dohme *et al*. (1999) reported that methane production decreased by 61% in defaunated rumen fluid. Iqbal *et al*. (2008) summarized the mechanisms in which defaunation reduce ruminal methane production as follows: (i) reduced fibre digestion, (ii) reduced methanogen population associated with protozoa, (iii) reduced inter specie hydrogen transfer, and (iv) increased partial pressure of oxygen in the rumen. Defaunation has been reported to adversely impact ruminal fibre digestion and negatively impact on animal production through a lowering of microbial protein out flow from the rumen (Moss *et al.*, 2000). Thus, the use of defaunating agents to reduce enteric methane production would have to be balanced against the effects of those agents on fibre digestion and protein metabolism in the rumen.

Bacteriocins

Bacteriocins are bactericidal peptides from bacteria that can be used according to Klieve and Hegarty (1999) to directly suppress methanogens. Callaway *et al*. (1997) reported an increase in propionate production and a 36% reduction in methane emissions when nisin, a bacteriocin from *Lactococcus lactis* was included into samples for *in vitro* analysis. *In vivo* studies revealed no effect on acetate: propionate ratio of cattle fed a diet containing nisin as additive (Mantovani and Russel, 2001). These authors contributed the lack of response to the degradation of nisin in the rumen or the adaptation of methanogens to develop resistance. Bovicin HC5, a bacteriocin from *Streptococcus bovis* was shown to inhibit *in vitro* methane emission by as much as 50% (Lee *et al.*, 2002). Bacteriocins could play a significant role in methane mitigation strategies if it could be produced by bacteria that inherently reside in the rumen and that will actively secrete these compounds (Kumar *et al.*, 2009).

Methane oxidizers

Methane oxidizing bacteria have been isolated from the hindgut of pigs (Moss *et al.*, 2000). These bacteria convert enteric methane to carbon dioxide. Valdes *et al*. (1997) conducted *in vitro* studies and observed a decreased accumulation of methane when methane oxidizing bacteria was added to ruminal fluid. The validity of this approach still needs to be tested *in vivo* and requires further research. However, the implication of methane oxidizers seems impractical as they need oxygen for growth (Kumar *et al.*, 2009).

Improving animal efficiency

The concept of increasing animal productivity to reduce methane emissions from ruminants is based on the maintenance of overall production output and as a result, increased production of useful product would mean that methane production per unit product will decline (Moss *et al.*, 2000; Mirzaei-Aghsaghali *et al*., 2015). However, a reduction in total methane output would only result if the levels of production remained constant and livestock numbers were reduced. This might be in contrast to food security policy and goals in developing countries.

As mentioned earlier, livestock in developing countries are mainly in extensive production systems and used for many purposes other than food production – as symbols of social status, for their religious values, for draft activities, for the energy of their manure, and as alternative sources of income. It might be difficult to convince farmers in developing countries to reduce their livestock numbers. In order for a mitigation strategy to be sustainable and effective it should consider all aspects of a specific production system. This illustrates the importance of developing country specific mitigation strategies or combinations of mitigation strategies. Possible options for increasing animal efficiency include among others the selection between or within breeds, selecting larger but faster growing breeds or through the manipulation of dietary regimes (as discussed earlier).

Genetic selection

Genetic improvement of livestock is a particularly cost effective technology, producing permanent and cumulative changes in performance (Wall *et al.*, 2009). The selection for productivity and efficiency helps to mitigate greenhouse gases in two ways: (i) higher productivity leads to higher gross efficiency because of diluting the maintenance cost of animals; and (ii) a given level of production can be achieved with fewer higher yielding animals (Wall *et al.*, 2009).

Wall *et al*. (2009) reported variations between animals, between breeds, and across time, providing potential for improvement through genetic selection. Genetic variation in feed intake also exists, independent of live weight and average daily gain and this variation provides a basis for genetic selection for feed-use efficiency in animals (Iqbal *et al.*, 2008). Arthur *et al*. (2001) reported that cattle with a lower DMI than their peers of equivalent live weight and ADG have a low residual feed intake (RFI) and are more feed efficient. Residual feed intake is calculated as the difference between actual feed intake and the expected feed requirements for maintenance of body weight and a certain level of production (Hegarty *et al.*, 2007). Nkrumah *et al*. (2006) reported that beef cattle with low residual feed intake produced up to 28% less methane than those with high residual feed intake. These authors attributed the lower methane production to differences in ruminal microbial population and stated that the differences could be heritable. Goopy and Hegarty (2004) ran trials with Angus steers and found large variations in methane emissions between animals at the same level of production and fed the same diet. These authors identified “high” and “low” methane emitters on identical feed and

feed intakes. The reason for the reported differences is unclear, but it was assumed that factors such as the rate of passage, microbial activity, fermentation conditions and grazing behaviour could play a role.

O'Hara *et al*. (2003) stated that as methane is produced through microbial activity, the animal could only have an impact on methanogenesis by interacting with microbes. Microbes respond to changes in substrate so the interaction could be via diet selection. The interaction could also be through the control of ruminal conditions via processes such as saliva secretion, salivary proteins, feed processing, and changes in rumen volume and digesta flow (O'Hara *et al.,* 2003). High methane emitting sheep have been reported to have large rumen volumes and slower digesta flow rates than low emitters (Pinaes-Patino *et al.,* 2003). Cows with persistent differences in rumen outflow rates were identified by Orskov *et al*. (1988) and these authors concluded that the differences were probably genetic in origin. Hegarty *et al*. (2007) concluded that the greatest methane abatement from selecting for residual feed intake would be achieved on diets with low digestibility.

Hormones

Bovine somatotropin and hormonal growth implants do not specifically reduce methane emissions but they can reduce emissions per unit of product through improved animal performance (Smith *et al.,* 2008). Bovine somatotropin (BST) is a genetically engineered metabolic modifier used to enhance the production of dairy cows (Moss *et al.,* 2000). It acts on the liver and kidneys to stimulate the production of insulin-like growth factors. Moss *et al*. (2000) reported a 15% increase in the productivity per animal when BST is administered which would give a reduction in methane output per unit product produced. The use of BST as a methane mitigation option is limited as there are consumer concerns and BST is banned in certain countries including the European Union.

Strategic supplementation

Mineral deficiencies in South African roughage sources are generally attributed to seasonal variations in areas where long dry winters occur and when natural grasses leaches and become less digestible and less nutritious (Boyazoglu, 1999). There appears to be a large variety of mineral imbalances present in South African soils especially of trace elements such as copper, zinc, magnesium, and manganese as well as phosphorous which is deficient in most regions in South Africa (Boyazoglu, 1999). To improve productivity, animals in all areas should have regular access to balanced mineral supplements. Correcting nutrient deficiencies may realize a net reduction in enteric methane emissions as it will improve animal production efficiency (Ominski and Wittenberg, 2004).

Water quality

Water quality can play a critical role in the production efficiency of animals (Ominski and Wittenberg, 2004). Willms *et al*. (2002) illustrated the impact of water quality on animal production through a series of trials. These authors observed that calves from cows drinking from a natural water source delivered through a trough (clean water) gained 9% more than calves from cows that had direct access to water from a pond. Heifers drinking clean water gained 23% and 20% more weight compared to heifers drinking directly from a pond and heifers drinking pond water pumped to a trough, respectively (Willms *et al.,* 2002). Thus, the improvement of animal performance through improved water quality management should serve to reduce methane output per unit product.

Conclusions and the need for future research

The increase in atmospheric concentrations of greenhouse gases, CO_2, CH_4, N_2O and others due to human activities is the main reason for accelerated climate change. The atmospheric concentrations of these greenhouse gases need to be brought to a steady state to avoid negative consequence due to the increased rate of climate change.

South Africa has a uniquely high carbon emitting profile for a developing county and ranked among the top 10 and 20 countries in the world regarding tons of carbon emitted per unit of gross domestic product annually and tons of carbon per capita in 1996, respectively (Scholes and van der Merwe, 1996). Projected climate changes over the next 50 years indicate a general aridification over the western and central regions with increased surface temperatures (DEA, 2015). Projected impacts on the agricultural sector proposed a fall in the net crop revenue by as much as 90% in 2100 (Boko *et al.*, 2007). Climate change could also have effects on the animal productivity through a reduction in feed quality and an increase in the occurrence of certain diseases.

The production of methane as a result of ruminal and hindgut fermentation accounts for an approximate 6 to 12% loss in gross ingested energy by ruminants depending on the basal diet. Methane yields are greater on pasture-based diets than for high grain-based diets, and it is higher from animals grazing C4 grasses compared to those grazing C3 grasses. Most South African pasture based ruminant production systems utilize C4 grasses.

Strategies to reduce methane from forage based production systems include feed management strategies such as the use of concentrates, the inclusion of legumes in forage mixtures, and feeding highly digestible forages. Strategies to increase animal efficiency through the manipulation of ruminal fermentation, strategic supplementation of minerals and through selection for animal variation have been discussed in the literature.

Many of these technologies designed to reduce methane from individual animals are geared towards altering diets of animals in intensive or feedlot management systems, which are less common in developing countries. There is a need to develop long term mitigation strategies as many of the present strategies have been found to be only effective for a limited period due to the adaptive capacity of ruminal microbes.

The identification of forages with low methane producing potential, cultivar selection, improved forage management, plant extracts and the use of fodder trees, legumes and alternative, drought resistant fodder species could have substantial potential as mitigation options and these may be best utilized in developing countries.

References

Afshar, M., Naser, M., Ali, M., Yahya, E., Mohammad, R.D. and Abolfazl, R.D., 2008. Estimation of methane production in sheep using nutrient composition of the diet. J. Anim. Vet. Adv. 7(6), 765 – 770.

Alcock, D. and Hegarty, R.S., 2006. Effects of pasture improvement on productivity, gross margin and methane emissions of a grazing sheep enterprise. Int. Congress Series 1293, 103 – 106.

Anderson, R.C., Carstens, G.E. and Miller., 2006. Effect of oral nitroethane and 2-nitropropanol administration on methane producing activity and volatile fatty acid production in the ovine rumen. Bioresour. Technol. 97, 2421 – 2426.

Archimède, H., Eugène, M., Marie Magdeleine, C., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P. and Doreau, M., 2011. Comparison of methane production between C3 and C4 grasses and legumes. Anim. Feed Sci. Technol. 166-167, 59-64.

Arthur, P.F., Archer, J.A., Johnson, D.J., Herd, R.M., Richardson, E.C. and Parnell, P.F., 2001. Genetic and phenotypic variance and covariance components for feed intake, feed efficiency, and other post weaning traits in Angus cattle. J. Anim. Sci. 79, 2805 – 2811.

Axelsson, J., 1949. The amount of produced methane energy in European metabolic experiments with adult cattle. Ann. R. Agric. Coll. Sweden. 16, 404 – 419.

Baker, S.K., 1998. Method for improving utilization nutrients by ruminants or ruminant like animals. Patent application: International publication number WO 95/11041.

Baker, S.K., Gnanasampanthan, G., Purser, D.B. and Hopkins, R.M., 1997. Immunogenic preparation and method for improving the productivity of ruminant animals. Patent application: International publication number WO 97/00086.

Baldwin, R.L., Thornley, J.H.M. and De Beever, D.E., 1987. Metabolism of the lactating cow. II. Digestive elements of a mechanistic model. J. Dairy Res. 54, 107 – 131.

Bannink, A., Kogut, J., Dijkstra, J. France, J., Kebreab, E., Van Vuuren, A.M. and Tamminga, S., 2006. Estimation of the stoichiometry of volatile fatty acid production in the rumen of lactating cows. J. Theor. Biol. 238, 36–51.

Bannink, A., 2007. Feeding strategies to reduce methane loss in cattle: Report 34, Animal Sciences group, Wageningen, February 2007.

BassirRad, H., Reynolds, J.F., Virginia, R.A. and Brunelle, M.H., 1998. Growth and root NO_3^- nad PO_4^{3-} uptake capacity of three desert species in response to atmospheric CO_2 enrichment. Aust. J. Plant Phys. 24, 353 – 358.

Bayaru, E., Kanda, S., Kamada, T., Itabashi, H., Andoh, S. and Nishida, T., 2001. Effect of fumaric acid on methane production, rumen fermentation, and digestibility of cattle fed roughage alone. J. Anim. Sci. 72, 139 – 146.

Beauchemin, K.A. and McGinn, S.M., 2006. Enteric methane emissions from growing beef cattle as affected by diet and level of feed intake. Canadian Journal of Animal Science 86, 401 – 408.

Beauchemin, K.A., Kreuzer, M., O'Mara, F. and McAllister, T.A., 2008. Nutritional management for enteric methane abatement: a review. Aust. J. Exp. Agric. 48, 21 – 27.

Benchaar, C., Calsamiglia, S., Chaves, A.V., Fraser, G.R., Colombatto, D., McAllister, T.A. nad Beauchemin, K.A., 2008. A review of plant derived essential oils in ruminant nutrition and production. Anim. Feed Sci. Technol. 145, 209 – 228.

Benchaar, C., Pomar, C. and Chiquette, J., 2001. Evaluation of dietary strategies to reduce methane production in ruminants: a modeling approach. Can. J. Anim. Sci. 81, 563 – 574.

Benchaar, C., Rivest, J., Pomar, C. and Chiquette, J., 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. J. Anim. Sci. 76, 617 – 627.

Bett, B., Kiunga, P., Gachoni, J., Sindato, C., Mbotha, D., Robinson, T., Lindahl, J. and Grace, D., 2017. Effects of climate change onhte occurrence and distrution of livestock diseases. Preventative Vet. Med. 137, 119 – 129.

Blaxter, K.L. and Clapperton, J.L., 1965. Prediction of the amount of methane produced by ruminants. Brit. J. Nutr. 19, 511 – 522.

Blaxter, K.L. and Wainman, F.W., 1964. The utilization of the energy of different rations by sheep and cattle for fattening. J. Agric. Sci. 63, 113 – 128.

Blignaut, J.N., Chitiga-Mabugu, M.R., Mabugu, R.M., 2005. Constructing a greenhouse gas inventory using energy balances: the case of South Africa for 1998. J Energy S. Afr. 16, 21 – 32.

Boadi, D. and Wittenberg, K.M., 2002. Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF_6) tracer gas technique. Can. J. Anim. Sci, 82, 201.

Boadi, D., Benchaar, C., Chiquette, J. and Massè, D., 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. Can. J. Anim. Sci. 84, 319 – 335.

Boadi, D., Wittenberg, K.M. and McCaughy, W.P., 2002. Effects of grain supplementation on methane production of grazing steers using sulphur hexafluoride (SF_6) tracer gas technique. Can. J. Anim. Sci. 82, 151 – 163.

Boadi, D.A., Wittenberg, K.M. and McCaughy, W.P., 2002b. Effects of grain supplementation on methane production of grazing steers using the sulphur (SF_6) tracer gas technique. Can. J. Anim. Sci. 82, 151 – 157.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Thabo, R., and Yanda, P., 2007. Africa. Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of working group II to the fourth Report of the International Panel on Climate change. Parry, M.L., Canziani, O.F., van der Linden, P.J. and Hanson, C.E. Eds., Cambridge University Press, Cambridge UK, 433 – 467.

Boyazoglu, P.A., 1999. Animal nutrition: concepts and applications. Van Schaik Publishers. P.p. 40.

Bratzler, J.W. and Forbes, E.B., 1940. The estimation of methane production by cattle. J. Nutr. 19, 511 – 522.

Broudiscou, L.P., Papon, Y. and Broudiscou, A.F., 2000. Effects of dry plant extracts on fermentation and methanogenesis in continuous culture of rumen microbes. Anim. Feed Sci. Technol. 87, 263 – 277.

Bruno, R.G.S., Rutigiiano, H.M., Cerri, R.Robinson, P.H. and Santos, J.E.P., 2005. Effect of feeding *Saccharomyces cerevisiae* yeast culture on lactation performance of dairy cows under heat stress in ruminant nutrition, feed additives and feedstuffs. J. Anim. Sci. 85, 310 – 326.

Busquet, M., Calsamiglia, S., Ferret, A., Cardozo., P.W., Kamel, C., 2005. Effects of cinnamaldehyde and garlic oil on rumen microbial fermentation in a dual flow continuous culture. J. Dairy Sci. 88, 2508 – 2516.

Callaway, T.R., Martin, S.A., Wampler, J.L., Hill, N.S. and Hill, G.M., 1997. Malate content of forage varieties commonly fed to cattle. J. Dairy Sci. 80, 1651 – 1665.

Calsamiglia, S., Busquet, M. and Cardozo, P.W., 2007. Invited review: essential oils as modifiers of rumen microbial fermentation. J. Dairy Sci. 90, 2580 – 2595.

Caro, D., Davis, S.J., Bastianoni, S. andCaldeira, K., 2017. Greenhouse gas emissions due to meat production in the last fifty years. In: Quantification of climate variability, adaptation and mitigation for agricultural stability (Ed. Mukhtan Ahmed and Claudio O Stockle). Springer International publishers, Switzerland.

Cattani, M., Tagliapietra, F., MAccarana, L., Hansen, H.H., Bailai, L. and Schiaven, S., 2014. Technical note: *In vitro* gas and methane production measurements from closed and ventilated rumen batch culture systems.J. Dairy Sci. 97 (3), 1736 – 1741.

Chagunda, M.G.G., 2013. Opportunities and challenges in the use of the laser methane detector to monitor enteric methane emissions from ruminants. Animal 7, 394 – 400.

Chagunda, M.G.G., Ross, D., Roberts, D.J., 2009. On the use of a laser methane detector in dairy cows. Computers and electronics in agriculture 68, 157 – 160.

Chaucheryras, F., Fonty, G., Bertin, G. and Gouet, P., 1995. *In vitro* H_2 utilization by a ruminal Acetogenic bacterium cultivated alone or in association with an archae methanogen is stimulated by a probiotic strain of Saccharomyces cerevisiae. Appl. Environ. Microbiol. 61, 3466 – 3497.

Chiquette J. and Benchaar, C., 2005. Effects of different dose levels of essential oil compounds on *in vitro* methane production by mixed ruminal bacteria. In: Ruminant nutrition: feed additives and feedstuffs. J. Dairy Sci 88, 306 – 315.

Cowling R.M., Rundel, P.W. and Desmet, P.G., 1998. Extraordinary high regional scale plant diversity in southern Africa arid lands: sub continental and global comparisons. Divers. Distrib,4, 27 – 36.

Czerkawski, J.W. and Breckenridge, G., 1977. Design and development of a long-term rumen simulation technique (Rusitec). Br. J. Nutr. 38, 371 – 384.

Danfaer, A., Huhtanen, P., Uden, P., Sveinbjornsson, J. and Volden, H., 2006. The Nordic dairy cow model, Karoline – Description. Pages 383 – 406. In: Kebreab, Dijkstra, France, Bannink and Gerrits (eds). Modelling nutrient utilization in farm animals. CAB International, Wallingford, UK.

DEA, 2014. Department of Environmental affairs: Greenhouse gas inventory of South Africa 2000 – 2010. Pretoria, South Africa.

DEA, 2015. Department of environmental affairs: South Africa's intended nationally determined contributions (INDC) – discussion document. Pretoria, South Africa.

DEAT, 2004. Department of environmental affairs and tourism: A national climate change response strategy for South Africa. Department of environmental affairs and tourism, September 2004, Pretoria.

DEAT, 2007. Scenario building team 2007. Long term mitigation scenarios: Technical summary. Department of Environmental affairs and tourism, Pretoria, October 2007.

Denman, S.E., Tomkins, N.W. and McSweeney, C.S., 2007. Quantification and diversity analysis of ruminal methanogenic populations in response to the antimethanogenic compound bromochloromethane. FEMS Microbiol. Ecol. 62, 12 – 322.

DeRamus, H.A., Clement, T.C., Giampola, D.D. and Dickison, P.C., 2003. Methnae emissions of beef cattle on forages: efficiency of grazing management system. J. Environ. Qual. 32, 269 – 277.

Dijkstra, J., Bannink, A., Van der Hoek, K.W. ans Smink, W., 2006. Simulation in variation in methane emissions in dairy cattle in the Netherlands. J. Dairy Sci. 89: Suppl. 1, 259.

Dijkstra, J., Kebreab, E., France, J. and Bannink, A., 2007. Modelling protozoa metabolism and VFA production in the rumen. Centre of nutrition modeling, University of Guelph, Canada.

Dijkstra, J., Neal, HD. St. C., Beever, D.E. and France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J. Nutr. 122, 2239 – 2256.

Dohme, F., Machmuller, A., Estermann, B.L., Pfistet, P., Wasserfallen, A. and Kreuzer, M., 1999. The role of rumen ciliate protozoa for methane suppression caused by coconut oil. Lett. Appl. Microbiol. 29, 187 – 193.

Dorman, D.H. and Deans, S.G., 2000. Antimicrobial agents from plants: Antimicrobial activity of plant oils. J. Appl. Microbiol. 88, 308 – 316.

Evans, J.D. and Martin, S.A., 2000. Effects of thymol on ruminal microorganisms. Curr. Microbiol. 41, 336 – 340.

Fievez, V., Dohme, F., Danneels, M., Raes, K. and Demeyer, D., 2003. Fish oils as potent rumen methane inhibitors and associated effects on rumen fermentation *in vitro* and *in vivo*. Anim. Feed Sci. Tech. 104, 41 – 58.

Garcia-Gonzalez, R., Lopez, S., Fernandez, R., Bodas, R. and Gonzalez, J.S., 2008. Screening the activity of plants and spices for decreasing ruminal methane production *in vitro*. Anim. Sci. Tech. 147, 36 – 52.

Garcia-Lopez, P.M., Kung, L Jr., Odom, J.M.I., 1996. *In vitro* inhibition of microbial methane production by 9,10-anthaquinone. J. Anim. Sci. 74, 2276 – 2284.

Gardiner, T.D., Coleman, M.D., Innocenti, F., Tompkins, J., Connor, A., Garnsworthy, P.C., Moorby, J.M., Reynolds, C.K., Waterhouse, A. and Wills, D., 2015. Determination of the absolute accuracy of UK chamber facilities used in measuring methane emissions from livestock. Measurement, 66, 272 – 279.

Goel, G., Makkar, H.P.S. and Becker, K., 2009. Inhibition of methanogens by bromochloromethane: effects on microbial communities and rumen fermentation using batch and continuous fermentations. Br. J. Nutr. 25, 1 – 9.

Goopy, J., Robinson, D., Woodgate, R., Donaldson, A., Oddy, H., Vercoe, P. and Hegarty, R., 2015. Estimates of repeatability and heritability of methane production in sheep using portable accumulation chambers. Anim. Prod. Sci. http://dx.doi.org/10.1071/AN13370.

Goopy, J.P. and Hegarty, R.S., 2004. Repeatability of methane production in cattle fed concentrate and forage diets. J. Anim. Feed Sci. 13, 75 – 78.

Grainger, C., Clarke, T., Auldist, M.J., Beauchemin, K.A., McGinn, S.M., Waghorn, G.C. and Eckard, R.J., 2009. Mitigation of greenhouse gas emissions from dairy cows fed pasture and grain through supplementation with *Acacia mearnsii* tannins. Can. J. Anim. Sci. 89 (2), 241 – 251.

Grainger, C., Clarke, T., McGinn, S.M., Auldist, M.J., Beauchemin, K.A., Hannah, M.C., Waghorn, G.C., Clark, H. and Eckard, R.J., 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF_6) tracer and chamber techniques. J. Dairy Sci. 90, 2755 – 2766.

Greening, R.C., Leedle, J.A.Z., 1989. Enrichment and isolation of Acetitomaculum ruminis, gen. nov., sp. Nov,: Acetogenic bacterai from bovine rumen . Arch. Microbial from the bovine rumen. Arch. Microbiol. 151, 399 – 406.

Griffith, D.W.T., Bryant, G.R., Hsu, D., Reisinger, A.R., 2008. Methane emissions from free ranging cattle: comparison of tracer and intergrated horizontal flux techniques. J. Environ. Qaul. 37, 582 – 591.

Hammond, K.J., Crompton, L.A., Bannink, A., Dijkstra, J., Yanez-Ruiz, D.R., O'Kiely, P., Kebreab, E., Eugene, M.A., Yu, Z., Shingfield, K.J., Schwarm, A., Hristov, A.N. and Reynolds, C.K., 2016. Review of current in vivo measurement techniques for quantifying enteric methane emissions from ruminants. Anim. Feed Sci. Technol. 219, 13 – 30.

Harborne, J.B., 1999. Classes and functions of secondary products from plants. In: Walton, N.J., Brown, D.E. (Eds.), Chemicals from plants: Perspectives on plant secondary products. World Scientific and Imperial College press, London, pp. 1 – 26.

Harper, L.A., Denmead, O.T., Freyney, J.R. and Byers, F.M., 1999. Direct measurements of methane emissions from grazing and feedlot cattle. J. Anim. Sci. 77, 1392 – 1401.

Hart, K.J., Martin, P.G., Foley, P.A., Kenny, D.A. and Boland, T.M., 2009. Effect of sward dry matter digestibility on methane production, ruminal fermentation and microbial population of zero-grazed beef cattle. J. Anim. Sci. 1910, 1786 – 1797.

Hegarty, R. nad Gerdes, R., 1998. Hydrogen production and transfer in the rumen. Rec. Adv. Anim. Nutr. 12, 37 – 44.

Hegarty, R.S., 1999. Reducing rumen methane emissions through elimination of rumen protozoa. Aust. J. Agric. Res. 50, 1321 – 1327.

Hegarty, R.S., 2004. Genotype differences and their impact on digestive tract function of ruminants: a review. Aust. J. Exp. Agric. 44, 459 – 467.

Hegarty, R.S. and Gerdes, R., 1998. Hydrogen production and transfer in the rumen. Rec. Adv. Anim. Nutr. 12: 37–44.

Hegarty, R.S., Goopy, J.P., Herd, R.M., and McCorkell, B., 2007. Cattle selected for lower residual feed intake have reduced daily methane production. J. Anim. Sci. 85, 1479 – 1486.

Hess, H.D., Kreuzer, M. And Diaz, T.E., 2003. Saponin rich tropical fruits affect fermentation and methanogenesis in faunated and defaunated rumen fluid. Anim. Feed Sci. Technol. 109, 79 – 94.

Hess, H.D., Mera, M.L., Tiemann, T.T., Lascano, C.E. and Kreuzer, M., 2008. *In vitro* assessment of the suitability of replacing the low-tannin legume *Vigna unguiculata* with the tanniniferous legumes *Leucaena leacocephala*, *Flemingia marcophylla* or *Calliandra calothyrsus* in a tropical grass diet. Animal feed Sci. Technol. 147, 105 – 115.

Hess, H.D., Tiemann, T.T., Noto, F., Carculla, J.E. and Kreuzer, M., 2005. Strategic use of tannins as means to limit methane emission from ruminant livestock. Int. Cong. Ser. 1293, 164 – 167.

Hindrichsen, I.K., Wettstein, H.R., MacMuller, A. and Kreuzer, M., 2004. Enteric methane emissions from dairy cows fed various diets and the corresponding methane emission from slurry. Pages 280 – 281. In: Proc. Of the Intern. Conf. Greenhouse Gas Emission from Agriculture – mitigation options and strategies. A. Weiske (ed). Institute for energy and environment, Leipzig.

Hindrichsen, I.K., Wettstein, H.R., MacMuller, A., Jorg, B and Kreuzer, M., 2005. Effect of carbohydrate composition on methane emission from dairy cows and their slurry. Env. Monit. Assesnm, 107, 329 – 350.

Hobson, P.N., 1997. The rumen microbial ecosystem, 2nd edition. Hobson, P.N. and Stewart, C.S. (Eds.). Blackie Academic and Professional. London, U.K.

Holter, J.B. and Young, A.J., 1992. Methane prediction in dry and lactating cows. J. Dairy Sci. 75, 2165 – 2175.

Hope, A.P., Canty, T.P., Salawitch, R.J., Tribett, W.R. and Bennet, B.F., 2017. Forecasting global warming. In: Paris Climate Agreement: A beacon of hope. Springer International publishers, Switzerland. Pp: 51 – 113.

Hosu, S.Y., Cishe, E.N. and Luswazi, P.N., 2016. Vulnerability to climate change in the Eastern Cape province of South Africa: What does the future hold for smalholder crop farmers. Agrekon, 55 (1-2), 133 – 167.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adegosan, A.T., Yang, W., Lee, c., Gerber, P.J., Henderson, B. and Tricarico, J.M., 2013. Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91, 5045 – 5069.

Hristov, A.N., Oh, J., Giallongo, F., Frederick, T., Weeks, H., Zimmerman, P.R., Zimmerman, S.R. and Branco, A.F., 2015. The use of an automated system (GreenFeed) to monitor enteric methane and carbon dioxide emissions from ruminant animals. J. Visualized Exp. 103, e52904.

Huhtanen, P., Cabezas-Garcia, E.H., Utsumi, S. and Zimmerman, S., 2015. Comparison of methods to determine methane emissions from dairy cows in farm conditions. J. Dairy Sci. 98, 3394 – 3409.

IPCC, 2007. IPCC Third Assesment Report: Climate change 2007 – The scientific basis. Contribution of Working Group I to the Third Assesment Reort of the Intergovermental Panel on Climate Change (IPCC) Houghton J.T., Ding, Y., Griggs D.J., Noguer M., van der Linden P.J. and Xiaosu D. (Eds) Cambridge University Press, UK.

Iqbal, M.F., Cheng, Y., Zhu, W. and Zeshan, B., 2008. Mitigation of ruminant methane production: current strategies, constraints and future options. World J. Microbiol. Technol. 24, 2747 – 2755.

Janssen, P.H., 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. Anim. Feed Sci. Technol. 160, 1 – 22.

Jarvis, G.N., Strompl, C., Burgess, D.M., Skillman, L.C., Moore, E.R.B. and Joblin, K.N., 2000. Isolation and identification of ruminal methanogens from grazing cattle. Current Microbiol. 40, 327 – 332.

Jayanegara, A., Leiber, F. and Kreuzer, M., 2012. Meta-anaylsis ofhte relationship between dietary tannin level and methane formation in ruminants from *in vivo* and *in vitro* experiments. J. Anim. Physiol. Anim. Nutr. (Berl.) 96, 365 – 375.

Johnson, D.E. and Johnson, K.A., 2002. Recent developments in understanding enteric methane production by ruminants: Implications for mitigation, International Non-CO_2 GHG mitigation workshop, Washington DC, 2-3 December 2002.

Johnson, D.E. and Ward, G.M., 1996. Estimates of animal methane emission. Environ. Monit. Assess, 42, 133 – 141.

Johnson, D.E., Ward, G.M. and Ramsey, J.J., 1996. Livestock methane: Current emissions and mitigation potential. In: Nutrient management in food animals to enhance and protect the environment. E.T. Kornegay (Ed.) Lewis Publishers, New York, NY. Pp. 219 – 234.

Johnson, K., Huyler, M., Westberg, H., Pierce, C.S., Lamb, B. and Zimmerman, P., 1994. Measurement of methane emissions from ruminant livestock using a SF_6 tracer technique. Envirom. Sci. Tech. 28, 359 - 362.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483 – 2492.

Johnson, K.A., Westberg, H.H., Lamb, B.K. and Kincaid, R.L., 1997. Quantifying methane emissions from ruminant livestock and examination of methane reductions strategies. Ruminant livestock efficiency program annual conference proceedings, EPA, USDA.

Jones, G.A., McAllister, T.A., Muir, A.D. and Cheng, K.J., 1994. Effects of saifoin (*Onobrychus viviifolia Scop*) condensed tannins on growth and proteolysis by four strains of ruminal bacteria. Applied Environ. J. 60, 1374 – 1378.

Kamra, D.N., Agarwal, N. and Chaudhary, L.C., 2005. Inhibition of ruminal methanogenesis by tropical plants containing secondary plant compounds. In: Solvia, C.R., Takahashi, J., Kreuzer, M (Eds.). Proceedings of the 2nd International conference of greenhouse gasses and animal agriculture. ETH Zurich, Switzerland, pp. 102 – 111.

Kebreab, E., Clark, K., Wagner-Riddle, C. and France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci. 86, 135 – 158.

Kebreab, E., Mills, J.A.N., Crompton, L.A., Bannink, A., Dijkstra, J., Gerrits, W.J.J. and France, J., 2004. An integrated mathematical model to evaluate nutrient partition in dairy cattle between the animal and its environment. Anim. Feed Sci. Tech. 112, 131 – 154.

Kempton, T.J., Murray, R.M. and Leng, R.A., 1976. Methane production and digestion measurements in the grey kangaroo and sheep. Aust. J. Biol. Sci. 29, 209 – 214.

Kirchgessner, M., Windisch, W. and Muller, H.L., 1994. Mehtane release from dairy cows and pigs. Pages 399 – 402. In: Proc. 13th Symp. Energy metabolism of farm animals, Aguilera, J.F. (ed) EAAP publ. No 76 CSIS Publ. Service, Spain.

Kirchgessner, M., Windisch, W. and Muller, H.L., 1995. Nutritional factors for the quantification of methane production. Pages 333 – 348. In: Ruminant physiology: digestion, metabolism, growth and reproduction. Proc. 8th Int. Symp. On ruminant physiology. Von Engelhardt, W., Leonhard-Marek, S., Breves, G.F. and Gieske, D (eds). Ferdinand Enke Verlag, Stuttgart.

Klieve, A.V. and Hegarty, R.S., 1999. Opportunities for biological control of ruminal methanogenesis. Aust. J. Agric. Res. 50, 1315 – 1319.

Knapp, A.K., Hamerlynck, E.P. and Owensby, C.E., 1993. Photosynthetic and water relations responses to elevated CO_2 in the C4 grass, *Andropogon gerardii*. Int. J. Plant Sci. 154, 459 – 466.

Kohn, R.A. and Boston, R.C., 2000. The role of thermodynamics in controlling rumen metabolism. Pages 11 – 24. Modelling nutrient utilization in farm animals. McNamara, J.P., France, J. and Beever, D.E. (eds). CAB International, Wallingford, UK.

Kriss, M., 1930. Quantitative relations of the dry matter of the food consumed the heat production, the gaseous outgo and the insensible loss in body weight of cattle. J. Agric. Res. 40, 283 – 296.

Kumar, S., Puniya, A.K., Puniya, M., Dagar, S.S., Sirohi, S.K., Singh, K. and Griffith, G.W., 2009. Factors affecting rumen methanogens and methane mitigation strategies. World J Microbiol Biotechnol, 25, 1557 – 1566.

Kumar, V., Tandon, M. and Verma, M.P., 2008. Enviroment friendly dairy farming: Nutritional techniques for mitigation methane production from ruminants. Dairy Planner. 4 (11), 12 – 14.

Lanigan, G.W., Payne, A.L., Peterson, J.E., 1979. Antimethanogenic drugs and heliotropism europsceum poisoning in penned sheep. Aust. J. Agric. Res. 29, 1281 – 1291.

Lassey, K.R., Ulyatt, M.J., Martin, R.J., Walker, C.F. and Shelton, I.D., 1997. Methane emissions measured directly from grazing livestock in New Zealand. Atmospheric Environ. 31, 2905 – 2914.

Lee, S.S., Hsu, J.T. and Mantovani, H.C., 2002. The effect of bovicin HC5, a bacteriocin from *Streptococcus bovis* HC5, on ruminal methane production *in vitro*. FEMS Microbiol Lett. 217, 51 – 55.

Le-liboux, S. and Peyraud, J.L., 1999. Effect of forage particle size and feeding frequency on fermentation patterns and sites and extent of digestion in dairy cows fed mixed diets. Anim. Feed Sci. Tech. 76, 297 – 319.

Lescaot, P. and Sauvant, D., 1995. Development of a mechanistic model for rumen digestion validated using dual flux of animal acids. Reprod. Nutr. Developm. 35, 45 – 70.

Leuning, R., Baker, S.K., Jamie, I.M., Hsu, C.H., Klein, L., Denmead, O.T. and Griffith, D.W.T., 1999. Methane emission from free-ranging sheep: a comparison of two measurement methods. Atmos. Environ. 33, 1357 – 1365.

Liang, J.B., Terada, F. And Hamaguchi, I., 1989. Efficiency of using the face mask technique for the estimation of daily heat production of cattle. In: Y van der Honinh and W.H. Close (Ed.). Energy metabolism in farm animals. Pudoc, Waginingen, Netherlands.

Lila, Z.A., Mohammed, N. and Tatsuaka, N., 2004. Effect of cyclodextrin diallyl maleate production, ruminal fermentation and microbes *in vitro* and *in vivo*. J. Anim. Sci. 75, 15 – 22.

Liu, J.X., Hu, W.L., Guo, Y.Q., Wu, Y.M. and Ye, J.A., 2005. Effect of tea sapponins on methane emission and fermentation in the faunated and defaunated rumen fluids. In: Solvia, C.R., Takahashi, J., Kreuzer, M. (Eds.), 2nd International conference on greenhouse gases and animal agriculture – working papers. Publication series, vol. 27. Institute of Animal Science, ETH Zurich, pp. 432 – 435.

Lockyer, D.R. and Jarvis, S.C., 1995. The measurement of methane losses from grazing animals. Environ. Poll. 90, 383 – 390.

Lodman, D.W., Braine, M.E., Carmean, B.R., Zimmerman, P., Ward, G.M. and Johnson, D.E., 1993. Estimates of methane emissions from manure of U.S. cattle. Chemosphere 26, 189 – 199.

Lopez, S. and Newbold, C.J., 2007. Analysis of methane. In: Measuring methane production from ruminants. Makkar, H.P.S and Vercoe, P.E (Eds.) Springer. Pp. 1 – 15.

Lopez, S., Valdes, C., Newbold, C.J. and Wallace, R.J., 1999. Influence of sodium fumatate on rumen fermentation *in vitro*. Brit. J. Nutr. 81, 59 – 64.

Lovett, D., Lovell, S., Stack, L., Callan, J., Finlay, M., Conolly, J. and O'Mara, F.P., 2003a. Effect of forage/ concentrate ratio and dietary coconut oil level on methane output and performance of finishing beef heifers. Livest. Prod. Sci. 84, 135 – 146.

Lovett, D.K., McGilloway, D., Bortolozzo, A., Hawkins, M., Callan, J., Flynn, B. and O'Mara, F.P., 2006. *In vitro* fermentation patterns and methane production as influenced by cultivar and season of harvest of *Lolium perenne L*. Grass and forage Science 61, 9 – 21.

Maas, P.J., 1987. Testing the calculation of the nutritive value according to the NEL system of fresh grass with a high N content. MSc thesis Wageningen Agricultural University p.p. 24.

Mantovani, H.C. and Russel, J.B., 2001. Nisin resistance of *Streptococcus bovis*. Appl. Environ. Microbiol. 67, 808 – 813.

Machmuller, A., Ossowski, D.A., Wanner, M. and Kreuzer, M., 1998. Potential of various fatty acids to reduce methane release from rumen fermentation *in vitro* (Rusitec). Anim. Feed Sci. tech. 77, 117 – 130.

Margan, D.E., Faichney, G.J., Graham, McC. and Donnelly, J.B., 1982. Digestion of a ground and pelleted diet in the stomach and intestines of young sheep from two breeds. Aust. J. Agric. Res. 33, 617 – 627.

Margan, D.E., Graham, N., Minson, D.J., Searle, T.W., 1988. Energy and protein values of four forages, including a comparison of tropical and temperate species. Aust. J. Exp. Agric. 28, 729 – 736.

Martin, S.A., 1998. Manipulation of ruminal fermentation with organic acids: a review. J. Anim. Sci. 76, 3123 – 3132.

McCaughey, W.P., Wittenberg, K. and Corrigan, D., 1997. Methane production by steers on pasture. Can. J. Anim. Sci. 77, 519 – 524.

McCaughey, W.P., Wittenberg, K. and Corrigan, D., 1999. Impact of pasture type on methane production by lactating beef cows. Can. J. Anim. Sci, 79, 221 – 226.

McCrabb, G.J., Berger, K.T., Magner, T., May, C. and Hunter, R.A., 1997. Inhibiting methane production in Brahman cattle by dietary supplementation with a novel compound and the effects on growth. Austr. J. Agric. Res. 48, 323–329.

McCrabb, G.J. and Hunter, R.A., 1999. Prediction of methane emissions from beef cattle in tropical production systems. Aust. J. Agric. Res. 50, 1335 – 1339.

McGinn S.M., Beauchemin, K.A., Coates, T. and Colombatto, D., 2004. Methae emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast and fumaric acid. J. Anim. Sci. 82, 3346 – 3356.

McLean, J.A. and Tobin, G., 1987. Animal and human calorimetry. Cambridge University Press. New York.

Meissner, H.H., Scholtz, M.M. and Schonfeldt, H.C., 2012. The status, socio-economic and environmental impact, and challenges of livestock agriculture in South Africa. www.rmrdsa.co.za

Menke, K.H. and Steingass, H., 1988. Estimation of the energetic feed value obtained from chemical analysis and *in vitro* gas production using rumen fluid. Anim. Res. Develop. 28, 7 – 55.

Menke, K.H., Raab, L., Salewski, A., Steingass, H., Fritz, D. and Schneider, W., 1979. The estimation of digestibility and metabolizable energy content of ruminant feeding-stuff from the gas production when they are incubated with rumen liquor *in vitro*. J. Agric. Sci. 93, 217 – 222.

Miller, T.L. and Wollin, M.J., 2001. Inhibition of growth of methane producing bacteria of the ruminant forestomach by hydroxymethylglutaryl~SCoA reductase inhibitors. J. Dairy Sci. 84, 1445 – 1448.

Mills, J.A.N., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E. and France, J., 2001. A mechanistic model of whole tract digestion and methanogenisis in the lactating dairy cow: Model development, evaluation and application. J. Anim. Sci, 79, 1584 – 1597.

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E. and France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. J. Anim. Sci. 81, 3141 – 3150.

Minson, D.J. and Wilson, J.R., 1994. Prediction of intake as an element of forage quality. Pages 533 – 563 in: Forage quality, evaluation and utilization. G.C Fahey (ed.) ASA, Madison, WI.

Minson, D.J., 1981. Nutritional differences between tropical and temperate pastures. In: Grazing animals, Morley, F.W.H (ed.) Amsterdam, Elsevier: pp. 143 – 157.

Mirzaei-Aghsaghali, A., Maheri-Sis, N., Mirza-Aghazadeh, A., Ebrahimnezhad, Y., Dastouri, M.R. and Golshani, A.A., 2008. Estimation of methane production in sheep using nutrient composition of the diet. Journal of Animal and Veterinary Advances 7, 765 – 770.

Mirzaei-Aghsaghali, A., Maheri-Sis, N., Siadati, S.A. and Jalilnejad, N., 2015. Factors affecting mitigation of methane emission from ruminants: Management strategies. Ecologia Balkanica. 7 (1), 171 – 190.

Moate, P.J., Clarke, T., Davies, L.H. and Laby, R.H., 1997. Rumen gas and load in grazing dairy cows. J. Agric. Sci. 129, 459 – 469.

Moe, P.W. and Tyrell, H.F., 1979. Methane production in dairy cows. J. Dairy Sci. 62, 1583 – 1586.

Molano,G. and Clark, H., 2008. The effect of level of intake and forage quality on methane production by sheep. Aust. J. Exp. Agric. 48, 219 – 222.

Monteny, G.J., Bannink, A. and Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agri. Ecosyst. Environ. 112, 163 – 170.

Montmasson-Clair, G. and Zwane, M., 2016. Climate change adaption and agriculture in South Africa: a policy assessment. WWF-SA. South Africa.

Moss, A.R., 1993. Methane: global warming and production by animals. Chalcombe Publications. Kent, U.K. 105pp.

Moss, A.R., 1994. Methane production by ruminants – Literature review of I. Dietary manipulation to reduce methane production and II. Laboratory procedures for estimating methane potential of diets. Nutr. Abstr. Rev. (Ser B) 64, 785 – 806.

Moss, A.R., Jouany, J.P. and Newbold, J., 2000. Methane production by ruminants: its contribution to global warming. Ann. Zootech.49, 231 – 253.

Muck, R.E., Wilson, R.K. and O'Kiely, P., 1991. Organic acid content of permanent pasture grasses. Irish J. Agric. Res. 30, 143 – 152.

Murray, P.J., Gill, E., Balsdon, S.L. and Jarvis, S.C., 2001. A comparison of methane emissions from sheep grazing pastures with different management intensities. Nutr. Cycl. Agreocosyst. 60, 93 – 97.

Murray, P.J., Moss, A., Lockyer, D.R. and Jarvis, S.C., 1999. A comparison of systems for measuring methane emissions from sheep. J. Agric. Sci. 133, 439 – 444.

Murray, R.M., Bryant, A.M. and Leng, R.A., 1976. Rates of production of methane in the rumen and large intestine of sheep. Brit. J. Nutr. 36, 1 – 14.

Mwenya, B., Santosa Sar, C., Gamo, Y., Kobayashi, T. And Takahashi, J., 2004. Effect of including beta 1-4 galacto-oligosaccharides, lactic acid bacteria or yeast culture on methanogenesis as well as energy and nitrogen metabolism in sheep. Anim. Feed Sci. Technol. 115, 313 – 326.

Newbold, C.I., McIntosh, F.M. and Wallace, R.J., 1998. Changes in the microbial population of a rumen simulating fermenter in response to yeast culture. Can J. Anim. Sci. 78, 241 – 244.

Nkrumah, J.D., Okine, E.K., Mathison, G.W., Schmid, K., Li, C., Basarab, J.A., Price, M. A., Wang, Z. and Moore, S.S., 2006. Relationships of feedlot efficiency, performance and feeding behaviour with metabolic rate, methane production, and energy partitioning in beef cattle. J. Anim. Sci 84, 145 – 153.

O.Mara, F., 2004. Greenhouse gas production from dairying: Reducing methane production. Adv. Dairy Technol. 16, 295 – 309.

O'Hara, P., Freney, J. and Ulyatt, M., 2003. Abatement of Agricultural non-carbon dioxide greenhouse gas emissions: a study of research requirements. Ministry of Agriculture, New Zealand.

O'Kelly, J.C. and Spiers, W.W., 1992. Effect of monensin on methane and heat productions of steers fed lucerne hay. Aust. J. Agric. Res. 43, 1789 – 1793.

Offner, A. and Sauvant, D., 2006. Thermodynamic modeling of ruminal fermentations. Anim. Res. 55, 1 – 23.

Omar, J.A., 2004. Effect of different ionophore treatments on the same rumen metabolic measures of steers. Dirasat Agric Sci 31, 178 – 184.

Ominski, K.H. and Wittenberg, K.M., 2004. Strategies for reducing enteric methane emissions in forage-based beef production systems. Proceedings: "The science of changing climates – Impact on Agriculture, forestry and wetlands" July 20 – 23, 2004, University of Alberta, Alberta society of Agronomy, Animal Science and Soil science.

Orskov, E.R., 1986. Starch digestion and utilization in ruminants. J. Anim. Sci. 63, 1624 – 1633.

Orskov, E.R., Ojwang, I. and Reid, G.W., 1988. A study on consistency of differences between cows in rumen outflow rate of fibrous particles and other substrates and consequences for digestibility and intake of roughages. Animal Production, 47, 45 – 51.

Ovenell-Roy, K.H., Nelson, M.L., Westberg, H.H. and Froseth, J.A., 1998. Effects of barley cultivar on energy and nitrogen metabolism of lambs. Can. J. Anim. Sci. 78, 389 – 397.

Patra, A.K., Kamra, D.N. and Agarwal, N., 2005. Effect of species on rumen fermentation, methanogenesis and protozoa counts in *in vitro* gas production test. In: Solvia, C.R., Takahashi, J., Kreuzer, M (Eds.). Proceedings of the 2nd International conference of greenhouse gasses and animal agriculture. ETH Zurich, Switzerland, pp. 115 - 118.

Pedreira, M., Primavesi, O., Lima, M.A., Frighetto, R., de Oliveira, S.G. and Berchielli, T.T., 2009. Ruminal methane emission by dairy cattle in southeast Brazil. Sci. Agric. 66, 742 – 750.

Pelchen, A. and Peters, K.J., 1998. Methane emissions from sheep. Small ruminant research, 27, 137 – 150.

Pinares-Patino, C.S., Baumont, R. and Martin, C., 2003. Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. Can. J. Anim. Sci. 83, 769.

Pitt, R.E., Van Kessel, J.S., Fox, D.G., Pell, A.N., Barry, M.C. and van Soest, P.J., 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Anim. Sci. 74, 226 – 244.

Pospisilova, J. and Catsky, J., 1999. Development of water stress under increased atmospheric CO2 concentration. Biologia Plantarum 42, 1 – 24.

Reynolds, C.K., Humphries, D.J., Kirton, P., Kinderman, M., Duval, S. and Steinberg, W., 2013. Effects of incremental doses of 3-nitro-oxypropanol on methane production, digestion, and rumen parameters in lactating dairy cows. Adv. Anim. Biosci. 4(2), 261 – 273.

Rouviere, P.E. and Wolfe, R.S., 1988. Novel biochemistry of methanogenesis. J. Biol. Chem. 263, 7913 – 7916.

Russel, J.B., 1998. The importance of pH in the regulation of ruminal acetate to propionate ratio and methane production *in vitro*. J. Dairy Sci. 81, 3222 – 3230.

Santoso, B., Mwenya, B., Sar, C. and Takahashi, J., 2007. Methane production and energy partition in sheep fed Timothy silage or hay-based diets. JITV 12, 27 – 33.

Schils, R.L.M., Oudendag, D.A., van der Hoek, K.W., De Boer, J.A., Evers, A.G. and De Haan, M.H., 2006a. Broeikasgasmodule BBPR. Animal Sciences group, Praktijkrapport Rundvee 90.

Scholes, R.J. and van der Merwe, M.R., 1996. Greenhouse gas emissions from South Africa. S.A. Journal of Sci. 92, 220 – 222.

Shibatta, M. and Terada, F., 2010. Factors affecting methane production and mitigation in ruminants. J. Anim. Sci. 81 (1), 2 – 10.

Sigh, K. and Sigh, G.P., 1997. Effect of concentrate levels in diet of cattle on rumen microorganisms. Indian J Anim Sci 64, 349 – 350.

Simmons, R.E., Barnard, P., Dean, W.R.J., Midgley, G.F., Thuiller, W. and Hughes, G., 2004. Climate change and birds: perspectives and prospects from southern Africa. Ostrich: Journal of African Ornithology, 75, 295 – 308.

Smink, W., Bos, K.D., Fitie, A.F., Van der Klok, L.J., Rijm, W.K.J., Roelofs, G. and Van den Broek, G.A.M., 2003. Methaanreductie melkvee. Een onderzoeksrapport naar inschatting van de methaanproductie vanuit de voiding en naar de reductiemogelijkheden via de voiding van melkkoeien. FIS report, Wagenin.

Smith, L.C., de Klein, C.A.M. and Catto, W.D., 2008. Effect of dicyandiamide applied in a grandular form on nitrous oxide emissions from a grazed dairy pasture in Southland, Nez Zealand, N.Z. J. Agric. Res. 51, 387 – 396.

Soliva, C.R. and Hess, H.D., 2007. Measuring methane emission of ruminants by *In vitro* and *In vivo* techniques. In: Measuring methane production from ruminants. Makkar, H.P.S and Vercoe, P.E (Eds.) Springer. Pp.15 – 33.

Soliva, C.R., Hindrichsen, I.K., Meile, L., Kreuzer, M. and Machmuller, A., 2003. Effects of lauric and myristic acid on rumen methanogens and methanogenesis *in vitro*. Lett. Appl. Microbiol. 37, 35 – 39.

Solomon, S., Qin, D., Manning, M., Alley, R.D., Berntsen, T., Bindhoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., KAttsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A. and Wratt, D., 2007. Technical Summary. In: Climate Change 2007: The physical Science basis. Contribution of working group I to the fourth Assessment Report of the Intergovermental Panel on Climate Change [Soloman, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M and Miller, H.L (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Staerfl, S.M., Amelchanka, S.L., Kalber, T., Solvia, C.R., Kreuzer, M. and Zeitz, J.O., 2012. Effect of feeding dried high-sugar ryegrass (‘Abermagic’) on methane and urinary nitrogen emissions of primiparous cows. Livest. Sci. 150, 293 – 301.

Stige L.C.J., Stave, K.S., Chan, L., Ciannelli, N., Pretorelli, M., Glantz, H.R. and Stenseth, N.C., 2006. The effect of climate variation on agro-pastoral production in Africa. P. Natl. Acad. SCi. USA, 103,3049 – 3053.

Stumm, C.K., Gitzen, H.J., Vogels, G.D., 1982. Association of methanogenic bacteria with ovine rumen ciliates. Brit. J. Nutr. 48, 417 – 431.

Takahashi, J., Chaudhry, A.S., Beneke, R.G. and Young, B.A., 1999. An open-circuit hood system for gaseous exchange measurements in small ruminants. Small Ruminant Research 32, 31 – 36.

Tamminga, S., Bannink, A., Dijkstra, J. And Zom, R., 2007. Feeding strategies to reduce methane in cattle: Report 34, Animal science group, Wageningen University, Netheralnd.

Tezel, U., Pierson, J.A., Pavlostathis, S.G., 2006. Fate and effect of quaternary ammonium compounds on a mixed methanogenic culture. Water Res. 40, 3660 – 3668.

Thornley, J.H.m. and France, J., 2007. Mathematical models in agriculture, 2nd edt. CABI Publishing, Wallingford, UK.

Torrent J. and Johnson, D.E., 1994. Methane production in the large intestine of sheep. Pp 391 – 394 In: Aguilera J.F. (Compiler). Energy metabolism of farm animals: proceedings of the 13th symposium. Mojacar, Spain.

UNFCCC, 2006. United Nations Framework Convention on Climate Change Handbook. Bonn, Germany: Climate Change Secretariat.

Ulyatt, M.J., Lassey, K.R., Shelton, I.D. and Walker, C.F., 2002. Methane emission from dairy cows and wether sheep fed subtropical grass dominant pastures in midsummer in New Zealand. New Zealand J. Agric. Res. 45, 227 – 234.

Valdes, C., Newbold, C.J., Hillman, K. and Wallace, R.J., 1997. Los microorganisms metantrofos come agentes modifactdores de la fermentacion ruminal. ITEA 18, 157 – 159 (Translated).

Van Jaarsveld, A.S. and Chown, S.L., 2001. Climate change and its impacts in South Africa. Trends in Ecology and Evolution, 16, 13 – 14.

Van Laar, H. and van Straalen, W.M., 2004. Ontwikkeling van een rantsoen voor melkvee dat de methaanproductie reduceert. Schothorst Feed Research.

Van Nevel, C.J. and Demeyer, D.I., 1995. Feed additives and other interventions for decreasing methane emissions, in: Wallace R.J., Chesson, A (Eds.), Biotechnology in animal feeds and Animal feeding, VCH, Weinheim, pp. 329 – 349.

Van Soest, P.J., 1982. Nutritional ecology of the ruminant. Corvallis, Pregon. O. and B. Books Inc.

Veen, W.A.G., 2000. Veevoedermaatregelen ter vermindering van mathaanproductie door herkauwers. Schothorst Feed Research proefverslag. www.robklimaat.nl

Vermorel, M., 1995. Annual methane emissions of cattle in France: variations depending on animal type and level. Product. Anim. 8, 265 – 272.

Vlaming, J.B., 2008. Quantifying variation in estimated methane emissions from ruminants using the SF_6 tracer technique. PhD Thesis. Massey University, Palmerston North, New Zealand.

Waghorn, G.C., Douglas, G.B., Niezen, J.H., Mc Nabb, W.C. and Foote, A.G., 1998. Forages with condensed tannins – their nutritional value for ruminants. Proc. New Zealand Grassland Assoc. 60, 89 – 98.

Wall, E., Simm, G. and Moran, D., 2009. Developing breeding schemes to assist mitigation of greenhouse gas emissions. Animal 2009, 1 – 11.

Wallace, R.J. and Newbold, C.J., 1993. Rumen fermentation and its manipulation. The development of yeast culture as feed additives, in: Lyons T.P. (Ed.), Biotechnology in the feed industry, Alltech technical publications, Nicholasville, Kentucky, pp. 173 – 192.

Wang, B., Neue, H.U. and Samonte, H.P., 1997. Effect of cultivar difference ('IR72'; 'IR65598' and 'Dular') on methane emissions. Agri. Ecosys. Environ. 62, 31 – 40.

Ward, J.K., Tissue, D.T., Thomas, R.B. and Strain, B.R., 1999. Comparative responses of model C3 and C4 plants to drought in low and elevated CO_2. Global climate boil 5, 857 – 867.

Willms, W.D., Kenzie, O.R., McAllister, T.A., Colwell, D., Veira, D., Wilmshurst, J.F., Entz, T. and Olson, M.E., 2002. Effects of water quality and cattle performance. J. Range. Manage. 55, 452 – 467.

Wolin, M.J., Miller, T.L. and Stewart, C.S., 1997. Microbe-microbe interactions. In: The rumen microbial ecosystem: 467 – 491. Hobson, P.N. and Stewart, C.S. (Eds). Blackie Academic and Professional, London.

Wolpe, P. and Reddy, Y., 2015. The contribution of low-carbon cities to South Africa's greenhouse gas emissions reduction goals. Stockholm Environmental Institute, Seattle, USA.

Woodward, S.L., Waghorn, G.C., Ulyatt, M.J. and Lassey, K.R., 2001. Early indications that feeding *Lotus* will reduce methane emissions from ruminants, In: Proceedings of the New Zealand Society of Animal Production, 61, 23 – 26.

Xu, G., Liu, X., Wang, Q., Xiong, R. and Hang, Y., 2017. Effects of screenhouse cultivation and organic materials incorporation on global warming potentials of rice fields. Environ. Sci. Pollution Res, 24, 6581 – 6591.

Yan, T., Agnew, R.E., Gordon, F.J. and Porter, M.G., 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. Livest. Prod. Sci. 64, 253 – 263.

Yan, T., Mayne, C.s. and Porter, M.G., 2006. Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. Int. Congress Series, 1293, 123 – 126.

Zeleke, A.B., Clement, C., Hess, H.D., Kreuzer, M. and Solvia, C.R., 2005. Effect of foliage from multi-purpose trees and a leguminious crop residue on *in vitro* methanogenesis and ruminal N use. Int. Cong. Ser. 1293, 168 – 171.

Ziervogel, G., New, M., Archer van Gerderer, E., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. and Warburton, M., 2014. Climate change impacts and adaptations in South Africa. WIREs Clim. Change, 5, 605 – 620.

Zimmerman, P.R., 1993. System for measuring metabolic gas emissions from animals. United States Patent number US005265618A

Zimmerman, P.R. and Zimmerman, S.R., 2012. Method and system for monitoring and reducing ruminant methane production. United States Patent Number US20090288606 A1.

Chapter 2

Direct methane and nitrous oxide emissions of South African dairy and beef cattle

C.J.L. du Toit[1,3,#], H.H. Meissner[2] and W.A. van Niekerk[3]

[1] Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa

[2]189 van Riebeeck Avenue, Lyttelton Manor, Centurion, 0157, South Africa

[3] Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa

Abstract

The objective of this study was to estimate direct methane and nitrous oxide emissions of South African dairy and beef cattle in total and per province using the Tier 2 methodology of the Intergovernmental Panel on Climate Change (IPCC), but adapted for tropical production systems. Dairy and beef cattle in 2010 contributed an estimated 964 Giga gram (Gg) or 72.6% of the total livestock methane emissions in South Africa. Beef cattle in extensive systems were the largest contributor (83.3%), followed by dairy cattle (13.5%), and feedlot cattle (3.2%). The enteric methane emission factors for dairy cattle of 76.4 kg CH_4/head/year and 71.8 kg CH_4/head/year for concentrate fed and pasture-based production systems, respectively, were higher than those reported by other developing countries, as well as the IPCC default value of 46 kg CH_4/head/year for developing countries. The beef cattle methane emission factors were similar to those reported by other developing countries of 78.9 kg CH_4/head/year and 62.4 kg CH_4/head/year for commercial and emerging/communal cattle, respectively, but higher than the IPCC default value of 31 kg/head/year. Primarily because of cattle numbers, Eastern Cape recorded the highest dairy and beef cattle methane emissions, whereas Gauteng showed the highest feedlot methane emissions.

Keywords: methane, nitrous oxide, dairy cattle, beef cattle, feedlot
[#] Corresponding author: dutoitcjl@tut.ac.za

Introduction

Recently South African livestock producers have come under increasing pressure over the environmental impact of production systems. The FAO (2006) reported that livestock contributed an estimated 18% of global anthropogenic greenhouse gas (GHG) emissions. Livestock produce GHG's in the form of methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) and methane from manure management and manure deposited on pastures and veld (rangeland) by grazing animals. Agriculture, forestry and land use (corrected for carbon sink values) emitted an estimated 4.9% of South African GHG gases in 2004, which makes it the third largest GHG contributor in South Africa after the energy industry and industrial processes with 78.9% and 14.1%, respectively (DEAT, 2009). Livestock produced approximately 27% of the national methane gas total, mainly through enteric methane emissions from ruminants. Otter (2010) reported that livestock contributed 98% of the agricultural sector's methane emissions. Methane is a potent GHG that remains in the atmosphere for approximately 9 to 15 years and is 25 times more effective in trapping heat in the atmosphere than

CO_2 over a 100-year period (FAO, 2006; IPCC, 2006). Nitrous oxide has an atmospheric lifetime of 150 years and a global warming potential of 296 times that of CO_2 (IPCC, 2006).
O'Mara (2011) stated that livestock GHG emissions relate closely with ruminant numbers, particularly cattle. In 2004, commercial beef cattle contributed 45% and emerging/communal cattle 33% of the total enteric fermentation of 1225 Giga gram (Gg) CH_4 in South Africa with mature cows and bulls having the highest CH_4 emission factors for enteric fermentation (Otter, 2010).

South African livestock production is based on a unique combination of commercial (intensive and extensive) and emerging and communal (subsistence) production systems. The levels of productivity and efficiency in these production systems vary greatly in certain areas and it is important to distinguish between them when calculating GHG emissions. Methane production in livestock is influenced by several factors other than population numbers, including the size and productivity of animals, level of feed intake, diet composition, digestibility and quality of forage, forage species and cultivar, as well as variation among animals (Scholtz *et al*., 2012).

Previous inventories (Blignaut *et al*., 2005; DEAT, 2009; Otter, 2010) were conducted on a national scale utilizing IPCC default values (Tier 1 approach) for some or all of their emission calculations. These emission factors do not distinguish effectively between classes of animals, production efficiencies, and production systems. They are often based on assumptions of animals utilizing highly digestible diets as well as temperate forages (Mills *et al*., 2001) which are not representative of South African production systems.

It is important to generate accurate GHG baseline figures to develop South Africa's capacity to understand and reduce GHG emissions from the livestock sector. The objective of this paper, therefore, is to re-calculate the direct methane and nitrous oxide emissions of dairy and beef cattle production in South Africa, taking into consideration the uniqueness of the South African scenario and using a refined Tier 2 approach. The Tier 2 methodology seeks to define animals, animal productivity, diet quality and management circumstances to support a more accurate estimate of feed intake for use in estimating methane production from enteric fermentation (IPCC, 2006). It was also considered important to do separate calculations for provinces as provinces differ in vegetation or biomes and production systems which may require different approaches to mitigation recommendations.

Materials and Methods
The methodology utilized is based on the Australian national greenhouse account's National Inventory Report (ANIR, 2010), which contains Australian country-specific and IPCC default methodologies and emission factors. Emission factors specific to South African conditions and management systems were calculated where possible. A Tier 2 approach was adopted for all major cattle sectors, including dairy, beef and feedlot, in accordance with the IPCC Good Practice requirements (IPCC, 2006). The inventory was compiled on a provincial basis to reduce errors associated with averaging input data across areas with environmental, physical and managerial differences. The provincial totals were aggregated to produce national totals and the inventory was based on 2010 population data.

Enteric fermentation
The proportion of intake that is converted into methane is dependent on the characteristics of the animal, the quality and type of feed and the feed intake. South Africa is a country with diverse rainfall, temperature, and soil patterns (Smith, 2006), which gives rise to regional and seasonal variations in feed quality and quantity. Due to the heterogeneity of available feed types within South Africa it was

considered important to use methodologies that could reflect such differences and was developed under similar conditions as in Australia (ANIR, 2009).

Dairy cattle

Emissions from dairy cattle are based on commercial production systems. Cattle used for milk production in the emerging and subsistence farming sectors were incorporated under communal beef cattle emissions, since the milk yields are not high enough to meet the definition of a dairy cow. Data on provincial cow population figures and average daily milk production (10.5 kg/ day) were sourced from the commercial dairy industry and calculated from the number of dairy producers per province and the number of cows per producer (LACTO data, 2010). These figures were verified against the total annual milk production in 2010 (2.5 billion litres). The total number of dairy animals per province was then calculated according to the ideal herd composition of a 100 cow herd (Wasserman, 2005).

There are two major dairy production systems in South Africa, a total mixed ration (TMR)-based system and a pasture-based system. The live weight of all classes of animals according to the herd structure was calculated according to data reported by Banga (2009) for Holstein cattle and Jersey cattle in TMR-based and pasture-based production systems. Banga (2009) reported that the national commercial dairy herd is composed of approximately 60% Holstein-type breeds and 40% Jersey-type breeds. This ratio was utilized to calculate the live weight of animals used in the emission calculations. Live weights of animals per age group were confirmed by using a prediction equation according to the Von Bertalanffy growth function given by Bakker and Koops (1978) as:

$LW\ (kg) = M[1-\{1-(W_0/M)^{1/3}\}e^{-kt}]^3$

Where:

LW = live weight
M = mature weight (kg)
W_0 = birth weight (kg)
k = growth rate parameter
t = age (months)

Variables used in the above equation were sourced from Banga (2009) and dairy breed societies in South Africa. Parameters used to predict the live weight of the various classes of animals as reported by Banga (2009) are presented in Table 2.1.

Table 2.1 Parameters used to predict live weight for each breed type and production system (Banga, 2009)

	Concentrate		Pasture	
	Holstein	**Jersey**	**Holstein**	**Jersey**
Birth weight (kg)	40	30	40	30
Mature weight (kg)	650	500	600	450
Growth rate (*k*)	0.0885	0.0915	0.07625	0.089

The animal weight, weight gain, diet characteristics and management data used in the algorithms to calculate emissions are presented in Appendix A. Daily methane production was calculated according to the Australian National Inventory Report (ANIR, 2009) based on dry matter intake.

Dry matter intake (I) for each dairy cattle class was calculated according to Minson and McDonald (1987) from live weight and live weight gain data:

$I = (1.185 + 0.00454W – 0.0000026W^2 + 0.315LWG)^2 \times MR + MI$ ……. Equation 1

Where: I = Intake (kg DM/head/day)
W = weight in kg (Appendix A.1, 2)
LWG = Live weight gain in kg/day (Appendix A.1, 2)
MR = Metabolic rate when producing milk (SCA, 1990); 1.1 for cows in milk and 1 for all other classes.

Additional intake for milk production from lactating animals (MI) was included to give a total intake (kg DM/head/day):

$MI = MP \times NE / k_l / q_m / 18.4$……..…….…. Equation 2

Where: MP = milk production (kg/head/day) from LACTO data (2010).
NE = 3.054 MJ NE/kg milk (SCA, 1990)
k_l = 0.60 efficiency of use of ME for milk production (SCA, 1990)
q_m = metabolizability of the diet. (i.e. ME/GE). Calculated using the equation of Minson and McDonald (1987),
q_m = 0.00795DMD – 0.0014 (where DMD is expressed as a %). (Appendix A.1, 2 and B.4)

Assuming a gross energy content of DM of 18.4 MJ/kg (SCA, 1990) the gross energy intake (GEI) of all dairy cattle classes was calculated as the sum of intake (I) multiplied by 18.4 MJ/kg DM. Intake of animals relative to that needed for maintenance (L) was calculated as actual intake divided by maintenance intake (intake of a non-lactating animal with live weight gain set to zero):

$L = I / (1.185 + 0.00454W – 0.0000026W^2 + (0.315 \times 0))^2$…...……. Equation 3

Blaxter and Clapperton's (1965) equation was used to calculate the percentage of GEI that is yielded as methane (Y):

$Y = 1.3 + 0.112DMD + L(2.37 – 0.050DMD)$ ……..…… Equation 4

Where: DMD = dry matter digestibility (%) (Appendix A.1, 2 and B.4)
L = intake relative to that needed for maintenance

The total daily production of methane (M),(kg CH_4/ head/ day) was calculated as:

$M = Y / 100 \times GEI / F$……...…….. Equation 5

Where: F = 55.22 MJ/ kg CH_4 (Brouwer, 1965).
GEI = Gross energy intake (MJ/day)

Beef cattle

Population data for 2010 and the herd structure for commercial and communal beef cattle on a provincial basis were sourced from Statistics South Africa (Stats SA), the Department of Agriculture, Forestry and Fisheries (DAFF) and the Agricultural Research Council (ARC) of South Africa (StatsSA, 2010; DAFF, 2010; Van der Westhuizen and Theron, 2012, Pers. Comm., SA stud book, P.O.Box 270, Bloemfontein, 9300, South Africa).

South African beef cattle production systems are mainly extensive and based on veld (*i.e*. rangeland or natural pastures). Tainton (1981) divided veld in South Africa into three broad types, namely sweetveld, sourveld and mixed veld. The percentage of each veld type in each province was estimated according to a map produced by Tainton (1999). The seasonal variation in veld quality and digestibly was sourced from the literature (Dugmore and Du Toit, 1988; De Waal, 1990; O'Reagain and Owen-Smith, 1996).

The commercial beef herd is composed of approximately 70% medium frame cattle (Bonsmara type), 15% large frame and 15% small frame (Van der Westhuizen and Theron, 2012, Pers. Comm., SA stud book, P.O.Box 270, Bloemfontein, 9300, South Africa). Live weights for each frame type were calculated from weight data published by Meissner *et al*. (1983) and verified with cattle breed societies. The average live weight per beef cattle age group or class was estimated according to the ratio (above) of medium, large and small frame breed types (70:15:15). Communal cattle live weights were calculated from the commercial cattle weights with a 20% reduction, since communal cattle are more Sanga and Zebu types, fed on lower-quality diets and with lower intakes. Live weight, live weight gain, feed characteristics and management data used in the algorithms are presented in Appendix B.1 to B.5.

Dry matter intake for each beef cattle class was calculated according to the equation presented by Minson and McDonald (1987) (Equation 1). Feed intake increases during lactation. It was assumed that the intake of all breeding cows increased by 30% during the season in which calving occurs and by 10% in the following season (SCA, 1990) as energy requirement for milk production declines during the second half of lactation.

Additional intake for milk production (MA) was calculated as:

MA = (LC x FA) + ((1 – LC) x 1)……..……...…….. Equation 6

Where: LC = proportion of cows > 2 years lactating
FA = feed adjustment (1.3 during the season of calving and 1.1 during the following season)

Calving percentage of 62% for commercial cattle and 35% for communal cattle (Scholtz *et al.*, 2012) were used to calculate MA. A single calving season was used for commercial cattle and it was assumed that communal cattle would calve throughout the year. As feed dry matter has a gross energy concentration of 18.4 MJ/ kg (SCA, 1990), the DMI was converted to GEI (MJ/ day) by:

GEI = I x 18.4 …… Equation 7

The intake of cattle relative to that needed for maintenance (L) was calculated using equation 3. The percentage of GEI that is yielded as methane (Y) was calculated according to equation 4. Kurihara *et al*. (1999) developed an equation to calculate the total daily methane production (M), (kg/

CH_4/head/day) for animals grazing tropical pastures. This equation (equation 8) was used to calculate the methane production from commercial and communal cattle:

$M = (34.9 \times I - 30.8)/1000$……. Equation 8
Where: M = methane emissions (kg/ CH_4/ head/ day)
I = Intake

Feedlot cattle
The 2010 provincial data on cattle in feedlots were sourced from the South African Feedlot Association (SAFA, 2012). The feedlot enteric methane emission (Y), (MJ CH_4/ head/ day) calculations are based on intake of specific diet components using an equation developed by Moe and Tyrrell (1979):

$Y = 3.406 + 0.510SR + 1.736H + 2.648C$…… Equation 9
Where: SR = intake of soluble residue (kg/day)
H = intake of hemicellulose (kg/day)
C = intake of cellulose (kg/day)

Soluble residue intake, hemicellulose intake and cellulose intake were calculated from feedlot diet analysis (ANIR, 2010) and average DM intake taken as 8.5 kg DM/ day (SAFA, 2012 and industry experts) (Appendix C.1 to C.3). Total daily methane production (M), (kg CH_4/head/day) was calculated as:

$M = Y / F$…….. Equation 10
Where: F = 55.22 MJ/ kg CH_4 (Brouwer, 1965)

Feedlot calculations were based on the assumption that an animal will stay in the feedlot for approximately 110 days (three cycles per year).

Manure management
Methane production from manure management of dairy, beef, and feedlot cattle were calculated based on the approach of the IPCC (2006) using a combination of default IPCC and country-specific input values. The authors of the ANIR (2010) stated that high temperatures, high solar radiation and low humidity environments would dry manure rapidly and that methane production was likely to be negligible in manure of range-kept livestock. Gonzalez-Avalos and Ruiz-Suarez (2001) recorded a negligible amount of methane emitted from manure of cattle kept under conditions similar to those in South Africa and Australia. The Australian methodology calculated the manure emissions factor (MEF) of range-kept cattle in environments with an average temperature of 21°C as 1.4×10^{-5} kg CH_4/ kg DM manure, based on the results of Gonzalez-Avalos and Ruiz-Suarez (2001).

Dairy cattle
Methane emissions from manure originate from the organic fraction of the manure (volatile solids). Volatile solids (VS), (kg/head/day) for South African dairy cattle were calculated according to ANIR (2010) as:

$VS = I \times (1 - DMD) \times (1 - A)$ …..…… Equation 11

Where: I = dry matter intake calculated as described above
DMD = dry matter digestibility expressed as a fraction (Appendix: A.1, 2)
A = ash content of manure expressed as a fraction (assumed to be 8% of faecal DM)

The percentage of manure managed in different manure management systems in South Africa and the manure methane conversion factors (ANIR, 2010) for these systems are reported in Appendix A.3. Methane production from manure (M), (kg/head/day) was calculated as:

$M = VS \times B_o \times MCF \times p$…… Equation 12

Where: B_o = emissions potential (0.24 m^3 CH_4/ kg VS) (IPCC, 2006)
MCF = integrated methane conversion factor – based on the proportion of the different manure management systems and the MCF for warm regions (Appendix A)
p = density of methane (0.662 kg/m^3)

The integrated MCF for lactating dairy cattle in TMR-based production systems was calculated as 10.07% and 1% for all other classes of dairy cattle. In pasture-based production systems the integrated MCF for lactating cattle was calculated as 3.64% and 1% for all other classes of cattle.

Beef cattle

South African beef production systems are mainly extensive and manure is deposited directly onto pastures and not actively managed. Methane emissions from manure (M), (kg/head/day) of beef cattle were calculated according to the ANIR (2010) as:

$M = I \times (1 - DMD) \times MEF$…… Equation 13

Where: I = intake as calculated under enteric emissions (Equation 1)
DMD = dry matter digestibility across seasons (Appendix B.4)
MEF = emissions factor (kg CH_4/kg DM manure). The factor of 1.4×10^{-5} based on the work of Gonzalez-Avalos and Ruiz-Suarez (2001) was used.

Feedlot cattle

The high stocking density of animals in feedlots results in a build-up of manure, which may lead to the production of methane, especially when the manure is wet. The method of manure management at a feedlot influences the amount of methane that is emitted from it. South African feedlots manage manure mainly by dry packing, which results in only a small fraction of potential methane emissions being generated (IPCC, 1997). The Australian national inventory (ANIR, 2010) reported default values for drylot methane conversion factors (MCF) of 1.5% based on the IPCC (1997). The volatile solid production for feedlot cattle was estimated based on data developed under the enteric methane emission calculations reported earlier.

The volatile solid production was calculated by equation 11 assuming a DMD of 80% for feedlot diets. The daily methane production from feedlot manure was then calculated using equation 12, assuming an emissions potential (B_0) of 0.17 m^3 CH_4/ kg VS (IPCC, 2006) and a MCF of 1.5% as stated above.

Nitrous oxide emissions

Dairy cattle

The methodology for calculating nitrous oxide (N_2O) emissions from dairy cattle is based on the calculation of crude protein input (CPI) and nitrogen storage (NR) based on the ANIR, (2010).
The crude protein intake of dairy cattle was calculated as:

$CPI = I \times CP$ ……. Equation 14

Where: I = DM intake (kg/day) calculated under enteric methane emission calculation (Equation 1)
CP = crude protein of feed intake expressed as a fraction (Appendix A.1, and A.2)

Nitrogen excreted in faeces (F) (kg/head/day) was calculated from the equation developed in Australia by the SCA (1990) and Freer *et al*. (1997) as:

$F = \{0.3(CPI \times (1 - [(DMD + 10/100])) + 0.105(ME \times I \times 0.008) + (0.0152 \times I)\}/ 6.25$... Equation 15

Where: DMD = dry matter digestibility expressed as a % (Appendix A.1 and A.2)
ME = metabolizable energy (MJ/ kg DM) calculated as: 0.1604DMD – 1.037 (Minson and McDonald, 1987)
I = dry matter intake (kg/ day) (Equation 1)
1/6.25 = factor of converting CP into nitrogen

Nitrogen retention (NR) was calculated as the amount of nitrogen in milk and body tissue and according to the ANIR (2010) as:

$NR = \{(0.032 \times MP) + \{0.212 - 0.008(L - 2) - [(0.140 - 0.008(L - 2)/ (1 + \exp(-6(Z - 0.4)))\}\} \times (LWG \times 0.92)\} / 6.25$ ……..….. Equation 16

Where: MP = milk production in kg/ day (LACTO data, 2010)
L = relative intake as calculated under the enteric methane section (Equation 3)
Z = relative size (live weight/ standard reference weight (Appendix A.5))
LWG = live weight gain (Appendix A.1 and A.2)

Nitrogen excreted through the urine (U, kg/head/day) was calculated according to the ANIR (2010) by subtracting NR, F and dermal protein loss from nitrogen intake:

$U = (CPI / 6.25) - NR - F - [(1.1 \times 10^{-4} \times W^{0.75})/ 6.25)]$ ……..……. Equation 17

The total annual faecal (AF), (Gg) and urinary (AU), (Gg) nitrogen excreted per head was calculated as:

$AF = (365 \times N \times F) \times 10^{-6}$ ……. Equation 18

$AU = (365 \times N \times U) \times 10^{-6}$ ……. Equation 19

The total emissions of nitrous oxide from the different manure management systems were then calculated according to the ANIR (2010) as:

Faecal $_{MMS}$ = (AF x MMS x $EF_{(MMS)}$ x C_g)……..……... Equation 20

Urine $_{MMS}$ = (AU x MMS x $EF_{(MMS)}$ x C_g) ……..……. Equation 21

Where: MMS = the fraction of manure managed in different manure management systems (Appendix A.3)
EF = emission factor (N_2O-N kg/ N excreted) for the different MMS (Appendix A.4)
Cg = 44/28 to convert elemental mass of N_2O to molecular mass

The total direct nitrous oxide emissions from dairy cattle were then calculated as the sum of faecal and urine MMS.

Beef cattle

Nitrous oxide emissions originating from beef cattle manure deposited on rangelands are not reported under livestock emissions (IPCC, 2006). The emission factor (kg N_2O-N/kg N excreted) is reported to be 0 (IPCC, 2006). According to the IPCC (2006), nitrous oxide emissions from manure deposited on pasture or veld is reported under the managed agricultural soils sections in the national inventory report format and not under livestock emissions. Nitrous oxide emitted from soil through the metabolism of urine and faeces deposited directly on pastures or veld was calculated according to the ANIR (2009).

Feedlot cattle

The methodology for calculating the nitrogen excretion of feedlot cattle is based on the ANIR (2009) and is similar to the N_2O calculations from dairy cattle. The crude protein intake of feedlot cattle (CPI), (kg/head/day) was calculated as:

CPI = NI x 6.25……. Equation 22

Where: NI = nitrogen intake (kg/day)
6.25 = factor for converting nitrogen into crude protein

Faecal nitrogen excretion (F), (kg/head/day) was calculated based on equations from SCA (1990) and Freer *et al*. (1997) as:

F = {0.3(CPI x (1 – [(DMD + 10/100])) + 0.105(ME x I x 0.008) + (0.0152 x I)}/ 6.25.. Equation 23

Where: DMD = dry matter digestibility expressed as a % (80%)
ME = metabolizable energy (MJ/kg DM) calculated as: 0.1604DMD – 1.037 (Minson and McDonald, 1987)
I = dry matter intake (kg/day) (8.5 kg DM/head/day)
1/6.25 = factor of converting CP into nitrogen

The amount of nitrogen retained in the body (NR), the nitrogen excreted in urine (U), and the total nitrous oxide emissions from feedlot cattle were calculated using equations 16 to 21 above.

Results and Discussion

The total methane emissions produced from South African livestock species in 2010 were estimated at 1328 Gg/year (Du Toit *et al*., 2012). Methane emissions from the South African cattle industries have been calculated as 964 Gg or 72.6% of the total livestock methane emissions during the same period. The contributions of dairy cattle, beef cattle on veld and feedlot cattle to the total cattle methane emissions were 13.5%, 83.3% and 3.2%, respectively. Otter (2010) reported the proportional contribution of dairy cattle as 14.31%, beef cattle on veld as 84.6% and feedlot cattle as 1.11% in

South Africa. In comparison, livestock in Brazil produced a total of 9937 Gg during 1995 with beef cattle producing 80.9% and dairy cattle 13.6% of the total livestock methane emissions (Lima *et al*., 2002). Indian livestock produced a total of 9093 Gg of methane in 2006 with beef cattle producing only 35.9%, buffalo 7.08% and dairy cattle 19.9% of the total livestock methane emissions (Swammy and Bhattacharya, 2006).

The direct GHG emissions from all cattle (dairy, commercial beef, communal beef and feedlot cattle) in South Africa are presented in Table 2.2 on a provincial basis. The Eastern Cape province has the highest methane emissions profile originating from cattle followed by KwaZulu-Natal, Free State and the North West, reflecting to a large extent the population numbers. Otter (2010) reported the total enteric methane emission of all cattle classes as 1050 Gg and the methane emitted from manure as 97.1Gg based on 2004 population data using the IPCC Tier 2 approach. The enteric methane emission figures calculated for 2010 correspond well with the figures reported by Otter (2010) but there is large variation in the methane emissions originating from manure. These differences may be owing to the methodologies employed to calculate volatile solid excretion and the manure management systems allocated to different types of cattle. Western Cape, Free State, Gauteng and North West have the highest nitrous oxide emissions originating from cattle. This is owing to the number of dairy and feedlot cattle in these provinces as well as differences in management systems among them.

Table 2.2 Provincial and total cattle methane and nitrous oxide emissions, 2010

	Enteric methane (Gg)	Manure methane (Gg)	Nitrous oxide (Gg)*
Western Cape	62.5	2.44	0.13
Eastern Cape	210	1.00	0.01
Northern Cape	49.9	0.12	0.01
KwaZulu-Natal	182	0.80	0.02
Free State	152	1.60	0.12
North West	115	0.87	0.08
Gauteng	29.2	0.52	0.11
Mpumalanga	92.8	0.51	0.04
Limpopo	63.5	0.12	0.02
Total	956	7.98	0.54

*N_2O emissions originating from fertilized pastures and faecal matter voided at pasture or veld is not included.
Gg: Giga gram.

The calculated methane emission factors (MEF) for South African dairy cattle are presented in Tables 3 and 4. Production systems based on concentrate feeds (TMR-based) have higher emission factors than pasture-based production systems except for the dry cow category. This is expected, owing to the higher digestibilities of concentrate-based diets as well as the higher intakes achieved by animals receiving concentrate diets. Lactating animals have the highest MEF, owing to increased energy requirements for production and differences in manure management systems compared with other dairy cattle classes.

Table 2.3 Direct methane and nitrous oxide emission factors for TMR-based dairy cattle, 2010

Animal class	Weight (kg)	$MEF_{enteric}$ (kg/h/year)*	MEF_{manure} (kg/h/year)*	N_2O (kg/h/year)*
Lactating cows	590	132	14.8	0.855
Lactating heifers	503	127	14.7	0.836
Dry cows	590	80.4	1.47	-
Pregnant heifers	394	67.7	1.24	-
Heifers >1 year	322	62.6	1.19	-
Heifers 6 - 12 months	172	42.1	0.75	-
Heifers 2 - 6 months	55	22.5	0.37	-
Calves	35	21.5	0.21	-

MEF: methane emissions factor.
* Kg/head/year

Table 2.4 Direct methane and nitrous oxide emission factors for pasture-based dairy cattle, 2010

Animal class	Weight (kg)	$MEF_{enteric}$ (kg/h/year)*	MEF_{manure} (kg/h/year)*	N_2O (kg/h/year)*
Lactating cows	540	127	4.98	0.029
Lactating heifers	438	116	4.80	0.027
Dry cows	540	83.4	1.11	-
Pregnant heifers	333	61.8	0.88	-
Heifers >1 year	254	52.6	0.78	-
Heifers 6 - 12 months	142	37.1	0.58	-
Heifers 2 - 6 months	54	24.5	0.40	-
Calves	36	20.0	0.32	-

MEF: methane emissions factor.
* Kg/head/year

The calculated enteric and manure methane emission factors for South African dairy cattle are higher than dairy cattle emissions factors in other developing countries such as Brazil, with 62 kg/head/year and 3 kg/head/year, respectively, and India, with 35.5 kg/head/year and 3.65 kg/head/year, respectively, as reported by Lima *et al*. (2002) and Chhabra *et al*. (2012). The IPCC (2006) reported enteric and manure methane emission default factors for Africa of 46 kg/head/year and 1 kg/head/year respectively. These figures are considerably lower than the national dairy herd average across all age groups of 76.4 kg/head/year and 71.8 kg/head/year for enteric emissions and 4.9 kg/head/year and 1.93 kg/head/year for manure emissions for TMR- and pasture-based production systems, respectively. These values are reported in Tables 3 and 4. South African calculated methane emission factors are more comparable with emission factors from developed countries for enteric and manure emissions such as the United Kingdom (109 and 28 kg/head/year), Australia (115 and 8.87

kg/head/year) and New Zealand (79.3 and 3.29 kg/head/year) as reported by ANIR (2010) and the New Zealand GHG Inventory (2010).

Table 2.5 reports on the dairy cattle total methane and nitrous oxide emissions on a provincial basis during 2010. The South African dairy industry consists predominantly of concentrate-based (TMR) production systems except for Eastern Cape and KwaZulu-Natal, which use mainly pasture-based production systems. Western Cape, Eastern Cape and KwaZulu-Natal are responsible for approximately 67.2% of the dairy industry's direct CH_4 emissions (Table 2.5). Approximately 81% of the total direct N_2O emissions of 0.31 Gg are produced in Western Cape, Free State and North West (Table 2.5). Nitrous oxide emitted from soil through the metabolism of faecal matter deposited directly on pastures by dairy cattle was estimated at 0.88 Gg on a national scale.

Table 2.5 Provincial and total methane (Gg) and nitrous oxide (Gg) emissions of dairy cattle based on 2010 data

Province	Population¤	Enteric methane (Gg)	Manure methane (Gg)	Nitrous oxide* (Gg)
Western Cape	338351	29.7	2.43	0.13
Eastern Cape	366197	30.3	0.96	0.005
Northern cape	13923	1.22	0.10	0.005
KwaZulu-Natal	282217	23.4	0.74	0.004
Free State	208624	18.3	1.50	0.08
North West	107627	9.44	0.77	0.041
Gauteng	46410	4.07	0.33	0.018
Mpumalanga	63648	5.58	0.46	0.024
Limpopo	12597	1.10	0.09	0.005
Total	1439594	123	7.38	0.31

¤ LACTO data (2010); Gg: Giga gram.
* N_2O emissions originating from fertilized pastures and faecal matter voided at pasture or veld is not included.

The South African beef industry is characterised by two distinct sectors, the commercial beef sector, including feedlot production systems, and emerging and communal (subsistence) production systems. These systems differ in breed type, feed availability, feed quality, level of production and production efficiency. The MEFs for commercial and communal beef production systems are reported in Tables 6 and 7, respectively. The emissions factors were calculated on a Tier 2 level (IPCC, 2006). Nitrous oxide emissions are not allocated to beef cattle, as the emission factor for manure deposited on veld (kg N_2O-N/ kg N excreted) is 0 and N_2O emission from manure deposited on veld and pasture is reported under the managed agricultural soils section in the national inventory report format (IPCC, 2006). Penttilä *et al.* (2013) reported that dung beetles could potentially increase GHG emissions from livestock faeces voided on rangeland or veld, mainly due to increased N_2O emissions. The possible effect of dung beetles is noted but not included in the present inventory due to insufficient data under South African conditions.

Table 2.6 Methane emissions factors for commercial beef cattle

Animal class	Weight (kg)	MEF_{entric} (kg/h/year)	MEF_{manure} (kg/h/year)
Bulls	733	113	0.022
Cows	475	92.6	0.018
Heifers	365	75.9	0.016
Oxen	430	89.4	0.018
Young oxen	193	51.6	0.012
Calves	190	51.6	0.012

MEF: methane emissions factor; kg/h/year: kg/head/year.

Table 2.7 Methane emissions factors for communal beef cattle

Animal class	Weight (kg)	MEF_{entric} (kg/h/year)	MEF_{manure} (kg/h/year)
Bulls	462	83.8	0.017
Cows	360	73.1	0.015
Heifers	292	62.5	0.013
Oxen	344	72.6	0.015
Young oxen	154	41.6	0.010
Calves	152	40.9	0.010

MEF: methane emissions factor; kg/h/year: kg/head/year.

Commercial cattle are heavier and have higher intakes of better quality diets than emerging sector and communal cattle. This results in higher MEF factors for commercial cattle. Although commercial cattle have higher MEF per head, they are more productive, and the methane emissions per kg product or per hectare should be lower than that of communal cattle.

The extensive beef cattle sector is the largest contributor to the cattle sector's GHG emissions contributing 54.7% and 28.6% for commercial and emerging/communal cattle, respectively. The Eastern Cape has the highest beef cattle methane emissions in both commercial and emerging/communal production systems, followed by KwaZulu-Natal, Free State and the North West (Table 2.8). Although nitrous oxide emissions from faecal matter voided on veld or pastures is not reported under livestock emissions according to the IPCC (2006) good practice guidelines, these emissions are reported to provide a more complete scenario of emissions associated with extensive beef production systems in South Africa. Nitrogen in faecal matter is primarily organic and must first be mineralized before it becomes a source of N_2O.

Table 2.8 Provincial and total methane emissions of extensive beef cattle based on 2010 data

Province	Commercial cattle			Emerging/Communal cattle		
	Population	Enteric methane (Gg)	Manure methane (Gg)	Population	Enteric methane (Gg)	Manure methane (Gg)
Western Cape	341892	21.5	0.0043	232108	11.2	0.0024
Eastern Cape	1873852	118	0.024	1272148	61.3	0.013
Northern Cape	603154	37.9	0.0074	207846	10.0	0.0021
KwaZulu-Natal	**1644534**	**103**	**0.021**	**1116466**	**53.8**	**0.012**
Free State	1341359	84.2	0.017	910641	43.9	0.009
North West	1049500	65.9	0.0132	712500	34.4	0.0073
Gauteng	14268	0.90	0.0002	244732	11.8	0.0026
Mpumalanga	887489	55.7	0.0012	602511	29.1	0.0064
Limpopo	638515	40.1	0.008	433485	20.9	0.0045
Total	8394563	527	0.096	5732437	276	0.059

Gg: Giga gram.

The mineralization process occurs at significant rates in higher rainfall regions. However, the decay of faeces in drier areas is much slower, with faeces remaining largely intact for months to years (ANIR, 2009). The N_2O emissions from faeces and urine voided on grazing was estimated at 1.3 Gg N_2O/year for commercial cattle and 0.61 Gg N_2O/ year for communal cattle on a national scale using emissions factors of 0.005 and 0.004 Gg N_2O-N/Gg N for faeces and urine, respectively, according to the ANIR (2009).

Feedlot cattle represent a small proportion of national cattle GHG emissions. This is owing to the relative small size of the industry and the duration the animals spend in a feedlot (approximately 110 days per cycle). The emission factors (kg/head/year) for feedlot cattle are presented in Table 2.9. Feedlot cattle have a relative high N_2O emission factor in relation to their manure methane emissions factor compared to dairy cattle.

Table 2.9 Direct methane and nitrous oxide emission factors for South African feedlot cattle

Animal Class	Ave Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)	N_2O* (kg/h/year)
Growing animal	335	58.9	0.87	0.457

MEF: methane emissions factor; kg/h/year: kg/head/year.
*N_2O emissions originating from fertilized pastures and faecal matter voided at pasture or veld is not included.

Gauteng represents approximately 42% of the total feedlot emissions, followed by Free State with 17.6% and North West with 17.4% (Table 2.9). The methane emissions from manure in the Western Cape and Eastern Cape are negligible and, owing to rounding of figures to two decimals, these figures are presented as 0.00 in Table 2.10.

Dry matter intake calculated for all cattle categories falls within the range reported by the IPCC (2006) of 1% - 3% of body weight (BW). Dairy cattle intake figures ranged from 1.52% to 4.8% of BW, commercial cattle intake from 1.3% to 2.6% of BW, communal cattle intake from 1.6% to 2.7% of BW and feedlot cattle intake was estimated at 2.5% of BW. Dairy cattle heifers 2 - 6 months and calves had a higher intake of 4.25% and 4.8% of BW, respectively. These intake figures correspond with intakes predicted for cattle of similar weight classes and production status in international sources (ANIR, 2010).

Table 2.10 Provincial and total GHG emissions of South African feedlot cattle based on 2010 data

Province	Population	Enteric methane (Gg)	Manure methane (Gg)	Nitrous oxide* (Gg)
Western Cape	3000	0.18	0.00[#]	0.0014
Eastern Cape	5000	0.29	0.00[#]	0.0023
Northern Cape	13000	0.77	0.01	0.0059
KwaZulu-Natal	33000	1.94	0.03	0.0151
Free State	89000	5.24	0.08	0.0407
Mpumalanga	41000	2.41	0.04	0.0187
Limpopo	23000	1.35	0.02	0.0105
Gauteng	211000	12.4	0.18	0.0964
North West	88000	5.18	0.08	0.0402
Total	506000	29.8	0.44	0.231

[#] Values too small to include.
*Values exclude N_2O emissions originating from fertilised pastures and faecal matter voided at pasture or veld.
Gg: Giga gram.

The averaged calculated emissions factors for all cattle have been compared to the IPCC (2006) default values for Africa (Table 2.11).

Table 2.11 Average calculated enteric methane emissions factors compared to IPCC default values for Africa (kg/head/year)

		South Africa	IPCC (2006)
Dairy cattle			
	TMR: lactating animals	130	46
	TMR: herd average	76.4	46
	Pasture: lactating animals	122	46
	Pasture: herd average	71.8	46
Beef cattle			
	Commercial	79	31
	Communal	62.4	31
	Feedlot	58.9	53*

*Feedlot IPCC EF sourced from North American category.
Dairy herd average excludes calve category (35kg live weight).

The calculated dairy cattle emission factors are considerably higher than the IPCC (2006) default emissions factors for Africa. The IPCC based their emission factors for commercial dairy cattle on animals grazing with low production (average milk production of 475 kg/head/year). The milk production of South African commercial dairy cattle ranges from approximately 3000 to 5000 kg/head/year (LACTO data, 2010). The emissions factors calculated for lactating dairy cattle are more comparable with the IPCC default values for North America (128 kg/head/year), Western Europe (117 kg/head/year) and Oceania (90 kg/head/year) (IPCC, 2006). The IPCC does not report on feedlot emission factors for Africa, but the calculated emission factors are in line with feedlot values reported for North America (Table 2.11). The calculated enteric emission factors of veld/extensive beef cattle range from 51.6 kg/head/year to 113 for commercial beef cattle and 40.9 - 83.8 kg/head/year for emerging/communal beef cattle with a herd average of 79 kg/head/year and 62.4 kg/head/year, respectively, which is higher than IPCC default values for Africa. These values correspond well with those for range kept beef cattle in Australia of 72 kg/head/year as reported by the ANIR (2010). The differences in the calculated emission factors and the IPCC default values are mainly because of variations in live weight and animal productivity used in the calculations. The IPCC calculated emission factors for Africa based on smaller, less productive cattle fed on low-quality diets, which are not representative of South African production systems.

The methane emission factors calculated for South African cattle are compared to other developing countries in Table 2.12. South African cattle emitted more methane annually than Brazilian and Indian cattle (Table 2.12). The dairy cattle emissions reported in Table 2.12 are for lactating animals only. The estimated enteric emission factors for South African cattle are higher across all cattle types compared with other developing countries, Brazil and India, which have smaller animals fed on lower-quality diets.

McGinn *et al*. (2007) and Loh *et al*. (2008) reported the enteric emission of feedlot cattle of Canada and Australia as 78.1 kg/head/year and 60.6 kg/head/year, respectively. Hegarty *et al*. (2007) reported the feedlot enteric methane emissions under Australian conditions as ranging from 51.8 kg/head/year to 69.4 kg/head/year. The calculated emission factor from South African feedlot cattle of 58.9 kg/head/year is in line with these values. Canadian feedlot cattle are mainly *Bos taurus*-type cattle.

South African feedlots contain a large percentage of *Bos indicus*-type cattle, which are well adapted to local conditions and should have lower MEF than *Bos taurus* cattle owing to lower intakes. Kurihara *et al*. (1999) measured emissions from *Bos indicus* cattle under feedlot conditions and fed high grain diets as 48.9 kg/head/year.

Table 2.12 Enteric methane emission factors for South African, Brazilian and Indian cattle

		South Africa		Brazil[1]	India[2]
		Commercial	Communal		
Dairy cattle	LW (kg)	438 - 590	-	400 - 414	175 - 300
	DMD (%)	76	-	55	55 - 62.5
	Milk production (kg/head/day)	10.5	-	1.08 - 3.3	1.7 - 5.7
	Enteric methane emission factor (kg/head/year)	116 - 132	-	59 - 65	28 - 43
Beef cattle	LW (kg): males	733	462	450	175 - 300
	LW (kg): females	475	360	280 - 400	
	LW (kg): young cattle	249	200	230	160
	DMD (%)	55.8*	55.8	50 - 56	55 - 62.5
	EF (kg/h/year): males	113	83.8	62 - 73	21 - 23
	EF (kg/h/year): females	92.6	73.1	65 - 73	
	EF (kg/h/year): young cattle	59.7	48.3	47 - 56	21 - 23

LW: Live weight; DMD: dry matter digestibility; EF: Emissions factor
*Value excludes the positive effect of supplementation on diet digestibility in commercial production systems.
[1] Lima *et al*., 2002.
[2]Swammy and Bhattacharya, 2006.

Conclusion

Cattle are a major source of methane emissions from the livestock sector in South Africa, contributing approximately 72.6% of the total livestock GHG emissions. Commercial beef cattle on veld are the major methane emitters, followed by emerging/communal beef cattle, dairy cattle and feedlot cattle. Dairy cattle are the major contributors to direct nitrous oxide emission from cattle. The methane emission factors calculated for commercial dairy and beef cattle production systems are more comparable to emission factors from developed countries (North America, Western Europe and Oceania) and the emerging/communal production systems to those of developing countries (Brazil and India). The IPCC default values for Africa underestimate emission factors across all cattle categories. The large variation in emission factors among countries and IPCC default values is primarily owing to differences in animal production systems, feed types, and nutrient use efficiency by animals. This emphasizes the need to develop country-specific emission factors for enteric and

manure emissions, as well as nitrous oxide emissions factors from manure through quantitative research.

Acknowledgements
This work is based on the research supported wholly by the National Research Foundation of South Africa and the RMRD SA.

References

ANIR, 2009. Australian National Inventory Report - Australian national greenhouse accounts: National Inventory Report. Department of climate change and energy efficiency, Commonwealth of Australia, Canberra, ACT.

ANIR, 2010. Australian National Inventory Report - Australian national greenhouse accounts: National Inventory Report. Department of climate change and energy efficiency, Commonwealth of Australia, Canberra, ACT.

Bakker, H. and Koops, W.J., 1978. An approach to the comparison of growth curves of Dutch Friesian, British Friesian and Holstein Friesian cows. In: Patterns of Growth and Development in Cattle. Eds: De Boer, H.and Martin, J., Current Topics in Veterinary Medicine, Vol 2. Springer Netherlands.pp. 705-915.

Banga, C.B., 2009. The development of breeding objectives for Holstein and Jersey cattle in South Africa. PhD thesis, University of the Free State, South Africa.

Blaxter, K.L. andClapperton, J.L., 1965. Prediction of the amount of methane production by ruminants. Br. J. Nutr. 19, 511-522.

Blignaut, J.N., Chitiga-Mabugu, M.R. and Mabugu, R.M., 2005. Constructing a greenhouse gas inventory using energy balances: the case of South Africa 1998. J. Energy S. Afr. 16, 21-32.

Brouwer, E., 1965. Report of sub-committee on constants and factors. In: Proc 3rd Symp Energy Metab. Ed: Blaxter, K.L., London: Academic Press. pp. 441-443.

Chhabra, A., Manjunath, K.R., Panigrahy, S. and Parihar, J.S., 2012. Greenhouse gas emissions from Indian livestock. Climate change, August, 2012.

De Waal, H.O., 1990. Animal production from native pasture (veld) in the Free State region – A perspective of the grazing ruminant. S. Afr. J. Anim. Sci. 20, 1-9.

DAFF, 2010. Department of Agriculture, Forestry and Fisheries - Livestock Population Statistics 2010. Pretoria.

DEAT, 2009. Department of Environmental Affairs and Tourism - Greenhouse gas inventory, South Africa. Communication under the United Nation Framework Convention on Climate Change. Pretoria, South Africa.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2012. The carbon and water footprint of the South African livestock Industry. RMRD SA Project: Progress report. www.RMRDSA.co.za

Dugmore, T.J. and Du Toit, J.H., 1988. The chemical and nutritive value of kikuyu pasture. S.Afr. J. Anim. Sci. 18, 72 – 75.
Erasmus, L., 2009. Milk production from cows grazing kikuyu-ryegrass pastures. MSc thesis, University of Pretoria, South Africa.

Erasmus, L.J., Smith, W.A. and Cronje, P.B., 2000. Feeding the lactating dairy cow to express its genetic potential In: Dairy Herd Improvement in South Africa. Eds: Loubser, L.F.B., Banga, C.B., Scholtz, M.M.and Hallowell, G.J., Agricultural Research Council, Animal Improvement Institute, Irene, South Africa.

FAO, 2006. Food and Agriculture Organization of the United Nations, 2010. [Accessed on 5 March 2012]. FAOSTAT.

Freer, M., Moore, A.D. and Donnelly, J.R., 1997. GRAZEPLAN: Decision support systems for Australian grazing enterprises – II. The animal biology model for feed intake, production and reproduction and the grazfeed DSS. Agric. Syst. 54(1), 77-126.

Gonzalez-Avalos, E. and Ruiz-Suarez, L.G., 2001. Methane emission factors from cattle manure in Mexico. Biosecure Technol. 80(1), 63-71.

Hegarty, R.S., Goopy, J.P., Herd, R.M. and McCorkell, B., 2007. Cattle selected for lower residual feed intake have reduced daily methane production. J. Anim. Sci. 85, 1479-1486.

IPCC, 1997. IPCC Third Assessment Report: Climate change 2001 – The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Eds: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J. and Xiaosu, D., Cambridge University Press, UK.

IPCC, 2001. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T.and Tanabe, K., Published: IGES, Japan.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

Kurihara, M., Magner, T., Hunter, R.A. and McCrabb, G.J., 1999. Methane production and energy partition of cattle in the tropics. Br. J. Nutr. 81, 227-234.

LACTO data, 2010. Milk Producers Statistics, MPO, Vol 14 (1). Pretoria, South Africa.

Lima, M.A., Young Pessoa, M.C.P. and Vieira Ligo, M.A., 2002. First Brazilian inventory of anthropogenic greenhouse gas emissions, background reports: Methane emissions from livestock. Ministry of Science and Technology, Brazil.

Loh, Z.M., Chen, D., Bai, M., Naylor, T., Griffith, D.W.T., Hill, J., Denmead, O.T., McGinn, S.M. and Edis, R.B., 2008. Measurement of greenhouse gas emissions from Australian feedlot beef

production using open path spectroscopy and atmospheric dispersion modelling. Aust. J. Exp. Agric. 48, 244-247.
McGinn, S.M., Flesh, T.K., Crenna, B.P., Beachemin, K.A. and Coates, T., 2007. Quantifying ammonia emissions from a cattle feedlot using a dispersion model. J. Environ. Quality 36, 1858-1590.

Meeske, R., Rothauge, A., Van der Merwe, G.D. and Greyling, J.F., 2006. The effect of concentrate supplementation on the productivity of grazing Jersey cows on a pasture based system. S. Afr. J. Anim. Sci. 36, 2.

Meissner, H.H., Hofmeyr, H.S., Van Rensburg, W.J.J. and Pienaar, J.P., 1983. Classification of livestock for realistic prediction of substitution values in terms of biologically defined Large Stock Unit. Technical communication, Department of Agriculture, Pretoria, Republic of South Africa.

Mills, J.A., Dijkstra, J., Bannik, A., Cammell, S.B., Krebreab, E. and France, J., 2001. A mechanistic model of whole tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation and application. J. Anim. Sci. 79, 1584-1597.

Minson, D.J. and McDonald, C.K., 1987. Estimating forage intake from growth of cattle. Trop. Grassl., 21(3), 116-121.

Moe, P.W. and Tyrell, H.F., 1979. Methane production in dairy cows. J. Dairy Sci. 62, 1583-1586.

New Zealand Greenhouse Gas Inventory, 2010. Agricultural sector 1990 - 2010: A Pickering and S Wear, Ministry of Agriculture and forestry, Ministry of the environment, New Zealand. http://www.mte.govt.nz/publications/climate/greenhouse_gas_inventrory/2012/index.html

O'Mara, F.P., 2011. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Anim. Feed Sci. Technol. 166-167, 7-15.

O'Reagain, P.J. and Owen-Smith, R.N., 1996. Effects of species composition and sward structure on dietary quality in cattle and sheep grazing South African sourveld. J. Agric. Sci. 127, 261-270.

Otter, L., 2010. The South African agricultural GHG inventory for 2004. Department of Agriculture, Forestry and Fisheries, South Africa.

Penttilä, A., Slade, E.M., Simojoki, A., Riutta, T., Minkkinen, K. and Roslin, T., 2013. Quantifying beetle-mediated effects on gas fluxes from dung pats. PloS One 8 (8), 1 – 7.

SAFA, 2012. South African Feedlot Association - Report to authors on provincial cattle numbers in feedlots. SAFA, Centurion, South Africa.

SCA, 1990. Standing Committee on Agriculture - 'Feeding standards for Australian livestock, Ruminants', CSIRO Publications, Australia.

Scholtz, M.M., Steyn, Y., Van Marle-Koster, E. and Theron, H.E., 2012. Improved production efficiency in cattle to reduce their carbon footprint for beef production. S. Afr. J. Anim. Sci. 42, 450-453.

Smith, B., 2006. Natural resources. In: The Farming Handbook. University of KwaZulu-Natal Press. South Africa.
Stats South Africa, 2010. Abstract of Agricultural Statistics, 2010. Directorate: Agriculture Statistics, DAFF, Pretoria, South Africa.

Swammy, M. and Bhattacharya, S., 2006. Budgeting anthropogenic greenhouse gas emission from Indian livestock using country specific emission coefficients. Current Science 91(10), 1340-1354.

Tainton, N.M., 1981. Veld Management in South Africa. Chapter 2: The ecology of the main grazing lands of South Africa. Pietermaritzburg: University of Natal Press.

Tainton, N.M., 1999. Veld Management in South Africa. Chapter 2: The ecology of the main grazing lands of South Africa. Pietermaritzburg: University of Natal Press.

Wasserman, J., 2005. Practical dairy tips. In: The Dairy Mail, February 2005, South Africa.

Appendix 2A

Table 2A.1 Dairy cattle activity data: Total Mixed Ration (TMR)

Animal class	Live weight (kg)	Live weight gain (kg/day)	DMD (%) [#]	Crude protein in feed (%)[#]
Lactating cow	590	0.1	76	17
Lactating heifer	503	0.55	76	17
Dry cow	590	0.1	60.3	13.5
Pregnant heifer	394	0.5	63	13.5
Heifer > 1 year	322	0.83	63	12
Heifer 6 - 12 months	172	0.78	68	16
Heifers 2 - 6 months	55	0.33	71	18
Calves	35	0.33	82	18

[#] Erasmus *et al*., 2000.
DMD: dry matter digestibility.

Table 2A.2 Dairy cattle activity data: pasture based

Animal class	Live weight (kg)	Live weight gain (kg/day)	DMD (%)*^				CP (%)*^
			Winter	Spring	Summer	Autumn	
Lactating cow	540	0.1	83	78	74	74	21.16
Lactating heifer	438	0.35	83	78	74	74	21.16
Dry cow	540	0.1	82	74	65.6	65.6	21.58
Pregnant heifer	333	0.35	82	74	65.6	65.6	21.58
Heifer >1 year	254	0.527	82	74	65.6	65.6	21.58
Heifer 6 - 12 months	142	0.622	82	74	65.6	65.6	21.58
Heifers 2 - 6 months	54	0.59	82	74	65.6	65.6	21.58
Calves	36	0.30	82	74	65.6	65.6	21.58

*Erasmus, L., 2009.
^ Meeske *et al*., 2006.
DMD: dry matter digestibility.
CP: crude protein.

Table 2A.3 Manure management systems for dairy cattle in South Africa

Manure management system (MMS)	Methane conversion factor (MCF, %)	TMR production system (%)	Pasture production system(%)
Lagoon	90	10	3
Liquid/slurry	35	0.5	0
Daily spread	0.5	1.0	7
Yielded at pasture	1	88.5	90

*MMS figures are based on DAFF (2009) data and expert assessments.

Table 2A.4 Emission factors used in algorithms for nitrous oxide (ANIR, 2009)

Manure management systems (MMS)	Emission factor (kg N_2O-N/ kg N excreted)
Lagoon	0.001
Liquid/ slurry	0.001
Daily spread	0
Pasture	0
Solid storage and drylot	0.02
Poultry manure with bedding	0.02
Poultry manure without bedding	0.005
Digester	0.001

Table 2A.5 Standard reference weight of dairy cattle

Animal class	Live weight (kg)
Lactating cow	580
Lactating heifer	580
Dry cow	580
Pregnant heifer	580
Heifer > 1 year	580
Heifer 6–12 months	580
Heifers 2–6 months	580
Calves	580

Appendix 2B

Table 2B.1 Commercial cattle live weights

Animal Class		Spring	Summer	Autumn	Winter
Bulls	LW (kg)	730	780	740	680
	LWG (kg)	0.55	0.55	-0.44	-0.66
Cows > 2 year	LW (kg)	410	500	470	450
	LWG (kg)	0.33	0.22	-0.33	-0.22
Heifers	LW (kg)	300	350	390	420
	LWG (kg)	0.22	0.55	0.44	0.33
Ox	LW (kg)	350	420	470	480
	LWG (kg)	0.6	0.77	0.55	0.11
Young ox	LW (kg)	75	160	240	295
	LWG (kg)	0.9	0.93	0.88	0.60
Calves	LW (kg)	75	160	235	290
	LWG (kg)	0.9	0.96	0.85	0.69

LW: live weight.
LWG: live weight gain.

Table 2B.2 Communal cattle live weights

Animal Class		Spring	Summer	Autumn	Winter
Bulls	LW (kg)	460	500	468	420
	LWG (kg)	0.44	0.44	-0.35	-0.53
Cows > 2 year	LW (kg)	364	380	356	340
	LWG (kg)	0.27	0.18	-0.27	-0.18
Heifers	LW (kg)	240	280	312	336
	LWG (kg)	0.44	0.44	0.36	0.27
Ox	LW (kg)	280	336	376	384
	LWG (kg)	0.48	0.62	0.44	0.09
Young ox	LW (kg)	60	128	192	236
	LWG (kg)	0.74	0.76	0.71	0.49
Calves	LW (kg)	60	128	188	232
	LWG (kg)	0.71	0.76	0.67	0.49

LW: live weight.
LWG: live weight gain.

Table 2B.3 Ratio of veld types per province

	Sweetveld	Sourveld	Mixed veld
Western Cape	0.5	0.3	0.2
Northern Cape	1	0	0
Eastern Cape	0.35	0.35	0.3
Free State	0.8	0.1	0.1
KwaZulu-Natal	0.2	0.6	0.2
Mpumalanga	0.15	0.7	0.15
Limpopo	0.6	0.2	0.2
Gauteng	0.2	0.6	0.2
North West	0.7	0.25	0.05

Veld: rangeland or natural pasture.

Table 2B.4 Veld digestibilities (%)

	Sweetveld	Sourveld	Mixed veld
Spring	65	65	65
Summer	60	60	60
Autumn	55	50	50
Winter	50	45	45

Veld: rangeland or natural pasture.

Table 2B.5 Beef cattle: standard reference weight (ANIR, 2009)

Animal Class	Standard reference weight (kg)
Bulls	770
Cows >2 year	550
Heifers	550
Ox	660
Young ox	660
Calves	660

Appendix C

Table 2C.1 Proportion of feedlot diet components in a total mixed ration

Feed component	Proportion
Total grain	0.779
Other concentrates	0.048
Grasses	0.138
Legumes	0.035

Table 2C.2 Fraction of cellulose, hemicellulose, soluble residue and nitrogen in feedlot diet components

Diet composition	Concentrates		Roughages	
	Grain	Other concentrates	Grass	Legume
Cellulose	0.07	0.19	0.31	0.36
Hemicellulose	0.04	0.11	0.31	0.20
Soluble residue	0.68	0.019	0.21	0.21
Nitrogen	0.02	0.05	0.026	0.032

Table 2C.3 Feedlot cattle: live weight (kg)

Feedlot cattle class	Entry weight (kg)	Exit weight (kg)	Standard reference weight* (kg)
Beef steer/ heifer	220 - 250	420	600

*Based on SCA (1990).

Chapter 3

Direct greenhouse gas emissions of the South African small stock sectors

C.J.L. du Toit[1,2#], W.A. van Niekerk[2] and H.H. Meissner[3]
[1] Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa
[2]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[3] 189 van Riebeeck Avenue, Lyttelton Manor, Centurion, 0157, South Africa

Abstract
There are increasing concerns about the impact of agriculture and livestock production on the environment. As a result, it is important to have accurate estimations of greenhouse gas (GHG) emissions if reduction measures are to be established. In this study, the direct GHG emissions from South African sheep and goats during 2010 were calculated. Calculations were done per province and in total. The Intergovernmental Panel on Climate Change (IPCC) methodology, adapted for tropical production systems, was used to calculate methane (CH_4) and nitrous oxide (N_2O) emissions on a Tier 2 level. Small stock is a key methane emission source in the South African livestock sector, and is responsible for an estimated 15.6% of the total livestock emissions. Small stock contributed an estimated 207.7 Giga gram (Gg) to the total livestock methane emissions in South Africa in 2010, with sheep producing 167 Gg and goats producing 40.7 Gg. Calculated enteric methane emission factors for both commercial and communal sheep of 8.5 kg/head/year and 6.1 kg/head/year, respectively, were higher than the IPCC default value of 5 kg CH_4/head/year for developing countries. A similar tendency was found with goat emission factors. The highest sheep and goat methane emissions were reported for the Eastern Cape province, primarily because of animal numbers.

Keywords: Greenhouse gas, methane, nitrous oxide, sheep, goats
[#]Corresponding author: dutoitcjl@tut.ac.za

Introduction

Agricultural activities contribute to greenhouse gas emissions through a variety of processes (Kebreab *et al*., 2006; Alemu *et al*., 2011; Archibeque *et al*., 2012; Scholtz *et al*., 2012). According to the Department of Environmental Affairs and Tourism (DEAT), agriculture, forestry and land use (corrected for carbon sink values) emitted an estimated 4.9% of the total South African GHG (greenhouse gas) emissions in 2004, making it the third largest greenhouse gas contributor after the energy sector (79%) and industrial processes (14%). Emissions from livestock are the largest contributor (98%) to methane emissions from the agricultural sector (Otter, 2010). Blignaut *et al*. (2005) reported that livestock was responsible for 41% of the total methane emissions in South Africa. The livestock sector contributes to GHG emissions through methane (CH_4) emitted directly from animals, and methane and nitrous oxide emitted from manure management. Methane emissions by ruminants are produced in the rumen during microbial fermentation of feed, especially carbohydrates, (Sallaku *et al*., 2011). The production of methane is associated with a loss of 2% - 14% of dietary energy (Johnson and Johnson, 1995; Sallaku *et al*., 2011). Methane and nitrous oxide have higher global warming potentials than carbon dioxide. Methane is 21 to 25 times more effective in trapping heat in the atmosphere, and nitrous oxide has a global warming potential of 296 to 310 times that of CO_2 (FAO, 2006; IPCC, 2006; ANIR, 2009). This makes agriculture and livestock an attractive target

for GHG reduction campaigns as small changes in agricultural emissions could result in large changes in total GHG emissions.

Methane production in livestock is influenced by several factors, including the level of feed intake, diet composition, digestibility and quality of forage, forage species and cultivar and variation among animals (Scholtz *et al*., 2012). Otter (2010) calculated the livestock emissions for South Africa in 2004 according to IPCC guidelines and reported livestock methane emissions as 1383 Giga grams (Gg) and nitrous oxide emissions as 11.8 Gg.

South African livestock production is based on a unique combination of commercial (intensive and extensive) and emerging and communal (subsistence) production systems. The level of productivity and efficiency between these two main production systems varies greatly in certain areas and it is important to distinguish between them when calculating GHG emissions. Sheep and goat farming is practised throughout South Africa, but is concentrated in the more arid regions such as Northern Cape and Eastern Cape provinces.

Previous inventories (Blignaut *et al*., 2005; DEAT, 2009; Otter, 2010) were conducted on a national scale utilizing IPCC default values (Tier 1 approach) for some or all of their emission calculations. These emission factors do not distinguish effectively between classes of animals, production efficiencies and production systems. They are often based on assumptions of animals utilizing highly digestible diets and temperate forages (Mills *et al*., 2001) that are not representative of South African production systems. Pelchen and Peters (1998) reviewed methane emissions from sheep, and found that estimations of the rate of methane emission from sheep vary widely among authors, which emphasises the use of country-specific emissions factors for inventory purposes.

The objective of this paper is to report the methane and nitrous oxide emissions of sheep and goat production systems in South Africa as calculated in total and per province. For that purpose, a Tier 2 approach was adopted, in contrast to previous estimates, which used primarily Tier 1. Direct emissions from enteric fermentation and manure management systems are presented.

Materials and Methods

The current inventory is based on small stock population data of 2010. A Tier 2 approach has been adopted for sheep and goat emission calculations in accordance with the IPCC (2006) good practice guidelines. The methodology employed to compile the inventory was also based on the Australian national greenhouse accounts, National Inventory Report (ANIR, 2009), which contains both Australian country specific and IPCC default methodologies and emission factors. Although the Australian methodology is based on that of the IPCC, it is adapted to Australian conditions, which are more representative of South African conditions. In addition, South Africa is a country with diverse climatic and growth conditions which influence seasonal feed quality, suited animal breeds to regions and production systems. Therefore, to attempt to reduce errors associated with averaging input data across areas with large physical and managerial differences, the inventory was conducted on a provincial basis. The provincial totals were aggregated to give national totals.

Population numbers were based on figures provided by the Abstract of Agricultural Statistics (Stats South Africa, 2010), Department of Agriculture, Forestry and Fishery statistics (DAFF, 2010) and relevant industry associations (Mohair South Africa, 2010; NGWA, 2010; Boerbok South Africa, 2011; South African Milch Goat Breeders Society, 2012). These figures were cross-referenced with slaughter data, wool production and milk production data for the same period.

Sheep

The South African sheep industry consists of a well-defined commercial sector and an emerging and communal sector (subsistence farmers). The emerging and communal small stock sectors were grouped under communal production systems. Population figures in each of these two sub-sectors were downscaled to the following breed types: Merino, other wool, non-wool and karakul breeds according to population data from statistics South Africa (Stats South Africa, 2010). The flock structures used in the emission calculations were based on an average South African flock structure (NWGA, 2011). It was assumed that the commercial and emerging/communal sectors would have similar flock structures. The flock structure consisted of older breeding rams (1%), breeding ewes (45%), young breeding rams (2%), young ewes (12%), weaned lambs (16%) and lambs (23%).

Sheep live weight per age group and breed type are reported in Appendix B.1 and B.2. The weight data were sourced from breed societies (NWGA, 2011; Afrino Breeders' Society of South Africa, 2011; Döhne Merino Breed Society of South Africa, 2011; Dorper sheep Breeders' Society of South Africa, 2011; Karakul Club, 2011; Merino Breeders' Society of South Africa, 2011; South African Mutton Merino breeders' Society, 2011) and compared with figures reported by Meissner *et al.* (1983). Communal animals are smaller, within a similar breed type, than commercial animals and a 20% weight reduction was assumed for emerging/communal animals compared with commercial animals across all age groups and breed types.

The natural rangeland (veld) in South Africa can be divided broadly into three main veld types in terms of grazing: sweetveld, sourveld and mixed veld. Sweetveld will remain palatable and nutritious even when mature, and can support animals throughout the year, whereas sourveld is palatable only during the growing season, and animals will typically lose weight when grazing sourveld in the dormant season. Mixed veld represents an intermediate between sweetveld and sourveld (Smith, 2006). The South African small stock industry is based predominantly on extensive grazing systems. The proportions of sweet, sour and mixed veld per province are reported in Table 3.1 (based on Tainton, 1999).

Table 3.1 Ratio of veld types per province (Tainton, 1999)

Province	Sweetveld	Sourveld	Mixed veld
Western Cape	0.5	0.3	0.2
Northern Cape	1.0	0	0
Eastern Cape	0.35	0.35	0.3
Free State	0.8	0.1	0.1
KwaZulu-Natal	0.2	0.6	0.2
Mpumalanga	0.15	0.7	0.15
Limpopo	0.6	0.2	0.2
Gauteng	0.2	0.6	0.2
North West	0.7	0.25	0.05

The quality of veld will vary according to veld type and season of use. The intake and methane production of animals will vary as the quality of veld changes through the seasons. The digestibility

of veld between and within veld types and between seasons was sourced from literature (Dugmore and Du Toit, 1988; De Waal, 1990; O'Reagain and Owen-Smith, 1996) and is reported in Table 3.2.

Table 3.2 Seasonal dry matter digestibilities (%) of South African veld types (Dugmore and Du Toit, 1988; De Waal, 1990; O'Reagain and Owen-Smith, 1996)

Season of use	Veld type		
	Sweetveld	Sourveld	Mixed veld
Spring	65	65	65
Summer	60	60	60
Autumn	55	50	50
Winter	50	45	45

Sheep and goats are selective grazers and browsers and will select for a higher quality diet. Commercial production systems employ supplemental feeding strategies that will improve the overall quality and utilization of the diet on offer. A 5% increase in the dry matter digestibility (DMD) reported in Table 3.2 was assumed for commercial small stock production systems to account for selective grazing and supplementation practices in the methane emissions calculations.

Sheep methane emissions estimates are based on Howden and Reyenga (1987), who reported a close relationship between dry matter intake (DMI) and methane production. Howden and Reyenga (1987) based their work on analysis of Australian respiration chamber experiments with sheep and found that DMI explained 87% of the variation in methane production of sheep.

The potential intake of sheep is dependent on body size and the metabolizability (ME/GE) of the diets received by the animals (ANIR, 2009). The potential intake of sheep (PI), (kg DM/head/day) is given by AFRC (1990) as:

$PI = (104.7q_m + 0.307W - 15.0)\ W0.75 / 1000$ ……..... Equation 1

Where: W = live weight (kg) (Appendix B.1; B.2)

q_m = metabolizability of the diet (ME/GE) = 0.00795DMD – 0.0014 (Minson and McDonald, 1987). Dry matter digestibility is expressed as a percentage (Table 3.2).

The average DMD of the various veld types and seasons is increased by 5% to allow for the selection of quality by sheep. Feed intake increases during lactation (ARC, 1980). It was assumed that 80% of commercial ewes and 50% of emerging/communal ewes will lamb during the year. Commercial production systems will employ two breeding seasons with 80% of the national flock lambing in autumn and 20% lambing in spring (L. Kruger, 2012, Pers. Comm., ARC-Animal Production Institute, Private bag X2, Irene, 0062, South Africa). This ratio was used for all provinces except Northern Cape, where only an autumn lambing season was assumed, and Western Cape, where a winter lambing season was assumed. It was assumed that communal production systems would lamb throughout the year (L. Kruger, 2012, Pers. Comm., ARC-Animal Production Institute, Private bag X2, Irene, 0062, South Africa). The intake of lactating animals was increased by 30% during the season in which lambing occurs (ANIR, 2009). Based on relationships presented by the SCA (1990) the additional intake for milk production (MA) was calculated as:

MA = (LE x FA) + ((1 – LE) x 1) ……. Equation 2
Where: LE = portion of breeding ewes lactating, calculated as the annual lambing rates x proportion of lambs receiving milk in each season (Appendix B.3)
FA = feed adjustment (assumed to be 1.3)

The daily methane production (M), (kg/head/day) was then calculated using intake figures generated from equation 1 based on the relationship published by Howden and Reyenga (1987):

M = I x 0.0188 + 0.00158 ……...……. Equation 3

Goats
The goat industry consists of a meat goat sector (commercial and communal), a milk goat sector and an Angora goat sector. Flock structures were assumed to be similar to the sheep flock structures and were verified by industry organizations (Boerbok South Africa, 2011; Mohair South Africa, 2011; M. Roets, 2012, Pers. Comm. P.O. Box 461, Scientific Roets, Kokstad, 4700, South Africa). The live weight of commercial goats was sourced from industry and experts (Boerbok South Africa, 2011; Mohair South Africa, 2011; Roets, 2004) and is reported in Appendices C.1 to C.4. The emerging/communal sector goats are assumed to be smaller and less productive than meat goats in the commercial sector and their live weights were based on commercial goat weights less 20%, similar to sheep calculations. It was assumed that milk goats and Angora goats are only farmed with commercially. Goats that are milked in the communal sector are mainly dual purpose and have a comparative low milk yield compared with commercial dairy goats. These goats were therefore incorporated into the emerging/communal meat goat class for the purpose of this inventory.

Dietary quality parameters used in the goat emission calculations were assumed to be similar to sheep diet quality for commercial and communal goat production systems across all seasons. The enteric methane emissions calculations for all goat breed types (meat, milk and Angora) followed the same methodology as for sheep based on the ANIR (2009). The enteric methane emissions were calculated using Equations 1, 2 and 3 above. Meat goat emission calculations were split into commercial and communal goats based on the population data (Stats South Africa, 2010; DAFF, 2010). It was assumed that lactating milk goats would receive a higher quality diet with a DMD of 70% throughout the year. Two kidding seasons, autumn and spring, were assumed for commercial meat goats with 80% of does kidding during the year. Communal meat goats are bred throughout the year with 50% of does kidding during the year. The ratio of kidding seasons between the provinces was similar to the ratio used for sheep production systems. Milk goat and Angora goat producers employ only a single autumn breeding season with 95% and 70% of does kidding in milk goats and Angora goats, respectively (Muller, 2005). The lactation feed adjustment was taken as 1.3 during the season of kidding and 1.1 during the season after kidding for milk goats.

Manure management

Manure methane
South African small stock production systems are mainly extensive, and manure is deposited directly onto pastures and veld/ rangeland with no active manure management occurring. Methane emissions from manure (M), (kg/ head/ day) of all categories of sheep and goats were calculated as:

$M = I \times (1 - DMD) \times MEF$ …….…… Equation 6

Where: I = Intake as calculated under enteric emissions

MEF = emissions factor (kg CH_4/ kg DM manure). The factor of 1.4×10^{-5} based on the work of Gonzalez-Avalos and Ruiz-Suarez (2001) was used.

The loss of animals owing to predators and stock theft is one of the major challenges for South African small stock producers. Some producers overnight sheep and goats in enclosures where manure deposition will be concentrated and managed in a drylot or compost system. Accurate data on the number of animals that overnight in enclosures are not available, and although this is noted, it is not incorporated into the inventory.

Nitrous oxide

Because sheep and goat production systems in South Africa are mainly extensive, the amount of nitrous oxide emitted from manure deposited on rangelands is minimal. Nitrogen in faecal matter is primarily organic and must first be mineralized before it becomes a source of N_2O. This process occurs at significant rates in regions with high rainfall. However, in dryer regions, decomposition of faeces is much slower, with faeces remaining largely intact for months to years (ANIR, 2009). Nitrous oxide emissions originating from faecal matter deposited directly on veld or pastures are not reported in this paper as these emissions are not recorded under livestock emissions according to the IPCC (2006) good practice guidelines, but under the managed agricultural soils section in the national inventory report format.

Results and Discussion

In 2010, direct methane emissions from South African livestock were estimated at 1328 Gg (Du Toit *et al*., 2012). The small stock industry produced an estimated 207.7 Gg of methane in the same year, with sheep producing 167 Gg and goats producing 40.7 Gg. The total small stock figure is higher than emissions calculated for 2004 of 167 Gg (Otter, 2010), despite a decrease in total population size from 2004 to 2010. The 2004 inventory was conducted on a Tier 1 level, utilizing IPCC (2000) default values for both sheep and goats. The present inventory was compiled on a Tier 2 level with emission factors calculated from country-specific data.

Sheep

The South African sheep population in 2010 was estimated to be 24.6 million with 65% of the national flock consisting of Merino and other wool-type breeds (Stats South Africa, 2010; DAFF, 2010). Commercial sheep are responsible for 90.6% of the total sheep emissions of 167 Gg, with emerging/communal sheep contributing 9.4%. Approximately 86% of the sheep are concentrated in the Eastern Cape, Northern Cape, Free State and Western Cape provinces. Merino sheep are the greatest contributors to sheep methane emissions, followed by non-wool breeds, other wool breeds and Karakul sheep with 81.7 Gg (49%), 48.3 Gg (29%), 36.5 Gg (21.9%) and 0.17 Gg (0.1%), respectively.

Table 3.3 Estimated methane emission factors for South African commercial sheep

Animal class	Merino			Other Wool			Non Wool			Karakul		
	Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)	Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)	Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)	Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)
Breeding rams	97.5	14.7	0.0042	138.0	22.2	0.0064	97.5	14.7	0.0041	72.5	10.5	0.003
Breeding ewes	53.0	8.07	0.0022	68.0	10.4	0.0029	63.5	9.66	0.0027	48.0	7.28	0.002
Young rams	78.3	11.5	0.0032	98.3	14.8	0.0042	68.3	9.88	0.0027	53.0	7.64	0.002
Young ewes	42.5	6.21	0.0016	55.5	8.01	0.0022	47.5	6.88	0.0018	40.5	5.94	0.0016
Weaners	37.5	5.54	0.0014	31.5	4.77	0.0012	37.5	5.54	0.0014	33.5	5.02	0.0013
Lambs	22.5	3.62	0.001	22.5	3.62	0.001	22.5	3.62	0.001	22.5	3.62	0.001

MEF: methane emissions factor; kg/h/year: kg/head/year

Table 3.4 Estimated methane emission factors for South African communal sheep

	Merino			Other Wool			Non Wool			Karakul		
Animal class	**Weight (kg)**	**$MEF_{enteric}$ (kg/h/year)**	**MEF_{manure} (kg/h/year)**	**Weight (kg)**	**$MEF_{enteric}$ (kg/h/year)**	**MEF_{manure} (kg/h/year)**	**Weight (kg)**	**$MEF_{enteric}$ (kg/h/year)**	**MEF_{manure} (kg/h/year)**	**Weight (kg)**	**$MEF_{enteric}$ (kg/h/year)**	**MEF_{manure} (kg/h/year)**
Breeding rams	78.0	10.5	0.0032	110.0	15.0	0.005	78.1	10.5	0.0032	58.0	7.62	0.0022
Breeding ewes	42.1	5.79	0.0017	54.5	7.4	0.0022	50.3	6.83	0.002	38.4	5.27	0.0015
Young rams	62.6	8.25	0.0025	59.5	10.5	0.0032	54.3	6.94	0.0021	42.4	5.6	0.0016
Young ewes	34.0	4.59	0.0013	44.0	5.80	0.002	38.0	5.07	0.0014	32.4	4.4	0.0012
Weaners	30.0	4.12	0.0011	25.0	3.55	0.001	30.0	4.12	0.0011	26.8	3.76	0.0010
Lambs	18.0	2.76	0.0007	18.0	2.76	0.0007	18.0	2.76	0.0007	18.0	2.76	0.0007

MEF: methane emissions factor; kg/h/year: kg/head/year.

Table 3.5 Estimated methane emissions of commercial sheep in South African according to provinces, based on 2010 population figures (Gg/year)

Breed Type		Western Cape	Northern Cape	Free State	Eastern Cape	KwaZulu-Natal	Mpumalanga	Limpopo	Gauteng	North West	Total
Merino	Population	1245804	2806729	2236117	3355781	353650	803167	118342	47704	320166	11287460
	Enteric methane	8.08	18.60	14.7	21.7	2.28	5.17	0.71	0.31	2.10	73.7
	Manure methane	0.0022	0.005	0.004	0.006	0.00061	0.001	0.0002	$8.2x10^{-5}$	0.0006	0.0197818
Other wool	Population	460721	1037980	826958	1241030	130786	297026	43765	17642	118403	4174312
	Enteric methane	3.58	8.23	6.52	9.63	1.01	2.29	0.34	0.14	0.93	32.7
	Manure methane	0.001	0.0023	0.0018	0.0026	0.0003	0.0006	$9.345x10^{-5}$	$3.697x10^{-5}$	0.0003	0.0089172
Non wool	Population	670854	1511398	1204129	1807058	190438	432498	63726	25688	172407	6078196
	Enteric methane	4.86	11.18	8.86	13.1	1.37	3.11	0.45	0.18	1.26	44.4
	Manure methane	0.001	0.003	0.002	0.004	0.0004	0.0008	0.0001	$5x10^{-5}$	0.00034	0.0118857
Karakul	Population	2761	6219	4955	7436	784	1780	262	106	709	25012
	Enteric methane	0.0163	0.0376	0.0297	0.0438	0.0046	0.0104	0.0382	0.0006	0.0042	0.1855
	Manure methane	$4.4x10^{-6}$	$1.01x10^{-5}$	$7.9x10^{-6}$	$1.2x10^{-5}$	$1.2x10^{-6}$	$2.8x10^{-6}$	$9.5x10^{-6}$	$1.6x10^{-7}$	$1.13x10^{-6}$	$4.9x10^{-5}$

Table 3.6 Estimated methane emissions of communal sheep in South African according to provinces, based on 2010 population figures (Gg/year)

Breed Type		Western Cape	Northern Cape	Free State	Eastern Cape	KwaZulu-Natal	Mpumalanga	Limpopo	Gauteng	North West	Total
Merino	Population	176022	396568	315945	474145	49968	113481	16721	6740	45237	1594827
	Enteric methane	0.84	1.95	1.54	2.24	0.23	0.53	0.10	0.03	0.22	7.68
	Manure methane	$2.4x10^{-4}$	$5.4x10^{-4}$	$4.3x10^{-4}$	$6.3x10^{-4}$	$6.6x10^{-5}$	$1.5x10^{-4}$	$2.7x10^{-5}$	$9x10^{-6}$	$6.1x10^{-5}$	$2.2x10^{-3}$
Other wool	Population	65096	146658	116842	175348	18479	41967	6184	2493	16729	589796
	Enteric methane	0.37	0.85	0.67	0.98	0.10	0.23	0.06	0.01	0.10	3.38
	Manure methane	$1.1x10^{-4}$	$2.4x10^{-4}$	$1.9x10^{-4}$	$2.8x10^{-4}$	$3x10^{-5}$	$6.8x10^{-5}$	$1.6x10^{-5}$	$4.02x10^{-6}$	$2.7x10^{-5}$	$9.7x10^{-4}$
Non wool	Population	94786	213548	170134	255323	26907	61109	9004	3630	24360	858801
	Enteric methane	0.50	1.16	0.91	1.33	0.14	0.32	0.07	0.02	0.13	4.58
	Manure methane	$1.4x10^{-4}$	$3.3x10^{-4}$	$2.6x10^{-4}$	$3.8x10^{-4}$	$4.01x10^{-5}$	$9.1x10^{-5}$	$1.9x10^{-5}$	$5.4x10^{-6}$	$3.7x10^{-5}$	$1.3x10^{-3}$
Karakul	Population	390	879	700	1051	111	256	37	15	100	3539
	Enteric methane	$1.7x10^{-3}$	$4x10^{-3}$	$3.1x10^{-3}$	$4.6x10^{-3}$	$4.8x10^{-4}$	$1.1x10^{-3}$	$1.6x10^{-4}$	$6.4x10^{-5}$	$4.4x10^{-4}$	$1.6x10^{-2}$
	Manure methane	$4.7x10^{-7}$	$1.1x10^{-6}$	$8.6x10^{-7}$	$1.3x10^{-6}$	$1.3x10^{-7}$	$3.1x10^{-7}$	$7.2x10^{-6}$	$1.8x10^{-8}$	$1.2x10^{-7}$	$1.2x10^{-5}$

The methane emission factors for commercial and emerging/communal sheep are presented in Tables 3 and 4. Other wool sheep (dual purpose breeds) have the highest methane emission factors (MEF) across all categories, followed by non-wool, Merino and Karakul sheep. Dual purpose rams have the highest overall MEF, 22.2 kg CH_4/head/year with an average of 10.6 kg CH_4/head/year across all animal classes (Table 3.3). Commercial Merino sheep make up approximately 46% of the national flock and have an average MEF of 8.26 kg CH_4/head/year, with rams yielding 14.7 kg CH_4/head/year and breeding ewes 8.07 kg CH_4/head/year. Emerging/communal sheep emissions are estimated to be 28% lower than those of commercial sheep (Table 3.4). The lower MEF of emerging/communal sheep is mainly owing to lower live weights and differences in the quality of diets offered to animals.

The provincial methane emissions for South African commercial and emerging/communal sheep during 2010 are presented in Table 3.5 and Table 3.6. The highest methane emissions were generated from the Eastern Cape, Northern Cape, Free State and Western Cape provinces, with 49, 42, 33 and 18 Gg respectively. These emission figures correspond with the population figures of sheep in the relevant provinces.

The enteric methane emission factors reported in Table 3.3 and Table 3.4 are higher than the IPCC (2006) default factors reported for sheep in Africa of 5 kg/head/year, but the manure emission factors are considerably lower than the IPCC (2006) default factors. The IPCC (2006) based emission factors on sheep with live weights of 45 kg for developing countries. The live weight of sheep in the commercial sectors (Table 3.3) is more representative of IPCC (2006) default factors for developed countries of 65 kg live weight and enteric methane emission factors of 8 kg/head/year. The IPCC (2006) default factors for developing countries are representative of the South African emerging/communal sector, although the calculated enteric methane emission factors for emerging/communal sheep are higher than the IPCC (2006) default factor of 5 kg/head/year (Table 3.4). The use of country-specific methane emission factors for manure emissions according to the Australian National Inventory Report (2009) methodology could explain the differences in calculated manure emission factors for both commercial and communal sheep and the IPCC (2006) default factors. Penttilä *et al.* (2013) reported that dung beetles could potentially increase GHG emissions from livestock faeces voided on rangeland or veld, mainly due to increased N_2O emissions. The possible effect of dung beetles is noted but not included in the present inventory due to insufficient data under South African conditions.

Table 3.7 Comparison of mean live weights and estimated average methane emission factors (kg/head/year) for sheep

		Live weight (kg)	Enteric CH_4	Manure CH_4
South Africa:				
Commercial	Merino	55.2	8.26	0.0023
	Other wool	74.1	10.6	0.007
	Non wool	56.1	8.37	0.0023
	Karakul	45.0	6.67	0.002
Communal	Merino	44.1	6.0	0.0043
	Other wool	45.1	7.51	0.0024
	Non wool	44.8	6.04	0.0035
	Karakul	36.0	4.9	0.0014
IPCC (2006)[1]				
	Developed countries	65.0	8.0	0.28
	Developing countries	45.0	5.0	0.15
Australia[2]		48.0	6.8	0.002
New Zealand[3]			11.0	0.11
UK [3]			5.0	0.11
India[4]	Male	30.4	4.0	0.18
	Female	30.4	4.0	0.18
China[5]	Breedable		7.1	
	Other		3.6	
Brazil[6]			5.0	0.15
Asia[5]			4.85	0.19

[1]IPCC (2006); [2] Australian National Inventory Report (2009); [3] New Zealand Greenhouse National Inventory Report (2010); [3] UK United Kingdom; [4] Sammy and Bhattacharya (2006); [5] Yamaji *et al*. (2003); [6] Lima *et al*. (2002).

The estimated methane emission factors are compared with published emission factors from developed and developing countries in Table 3.7. The average enteric emission factor for commercial sheep, including Karakul sheep, of 8.5 kg/head/year (9.09 kg/head/year excluding Karakul sheep) is higher than that of Australian sheep (6.8 kg/head/year) and sheep from the United Kingdom (5 kg/head/year), but lower than sheep emission factors from New Zealand (11 kg/head/year). These differences are likely to be owing to variations in age structures, breed types and diet qualities used to calculate the average emission factors from these sources. South African emission factors for sheep are not comparable with other developing countries such as India, Brazil, China and Asia (Table 3.7), mainly due to differences in live weights of sheep. Indian sheep are reported by Swammy and Bhattacharya (2006) to have enteric methane emissions of 4 kg/head/year with average live weights of 30.4 kg. These figures are comparable with the enteric emission factors of emerging/communal Karakul sheep with live weights of 36 kg and enteric methane emission factors of 4.9 kg/head/year.

The calculated dry matter (DM) intake of all categories of sheep is in the range of the IPCC (2006) guidelines of between 1% and 3% of body weight. Lassey (2007) measured enteric methane emission from sheep fed diets with similar digestibilities to South African diets using the SF_6 technique. The emission factors for South African sheep receiving diets of approximately 55% DMD are 0.41 g CH_4/kg LW/day and 0.39 g CH_4/kg LW/day for commercial and communal sheep, respectively. These figures are lower than those reported by Lassey (2007) of 0.45, 0.46 and 0.43 g CH_4/kg LW/ day for sheep fed diets of 61.2%, 54% and 69.3% DMD using the SF_6 technique.

Goats

Meat goats

The South African goat population of approximately 7 million animals consists of commercial and emerging/communal meat goats, Angora goats and milk goats comprising 24.6%, 60.8%, 14.3% and 0.3%, respectively of the total national goat population. Goats are farmed with throughout South Africa. The Eastern Cape and Limpopo provinces are the largest goat-producing provinces in South Africa (DAFF, 2011). The Boer goat, Savanna and Kalahari Red are recognized as commercial meat goat breeds with the Saanen, Toggenburg and British Alpine goats being kept mainly for milk production (DAFF, 2011). South Africa is the largest mohair producer globally (Mohair South Africa, 2011) with approximately 1 million Angora goats farmed with commercially, mainly in the Western Cape, Eastern Cape and Northern Cape provinces. The methane emission factors for commercial and communal meat goats are presented in Tables 8 and 9.

Table 3.8 Estimated methane emission factors for commercial goats in South Africa

Animal class	Weight (kg)	Intake (kg/day)	MEF $_{enteric}$ (kg/h/year)	MEF $_{manure}$ (kg/h/year)
Breeding bucks	118.0	2.6	18.3	0.02
Breeding does	78.0	1.67	12.1	0.013
Young bucks	88.3	1.8	13.1	0.014
Young does	55.5	1.08	8.01	0.0084
Weaners	37.5	0.72	5.54	0.006
Kids	22.5	0.44	3.62	0.0034

MEF: methane emissions factor; kg/h/year: kg/head/year.

Commercial goats have an average MEF of 10.1 kg CH_4/head/year, which is 37% higher than the average of 6.3 kg CH_4/head/year for emerging/communal goats. The higher emissions factors for all classes of commercial goats are due mainly to better selection, nutrition and health management, which give rise to heavier, more productive animals (Masika *et al*., 1998). Although the emissions per kg product were not calculated in this publication, commercial goats will have a lower MEF per kg product when compared with communal goats. The average methane emission factor for commercial goats of 0.42 g CH_4/kg LW/day is similar to the emissions of commercial sheep of 0.41 g CH_4/kg LW/ day. This trend is also present between the emerging/communal goats and sheep emission figures. The emerging/communal goat enteric methane emissions per day of 0.37 g CH_4/kg LW is slightly lower than that of emerging/communal sheep of 0.39 g CH_4/kg LW/day as reported earlier.

Table 3.9 Estimated methane emission factors for emerging/communal goats in South Africa

Animal class	Weight (kg)	Intake (kg/day)	MEF $_{enteric}$ (kg/h/year)	MEF $_{manure}$ (kg/h/year)
Breeding bucks	82.0	1.53	11.1	0.013
Breeding does	54.4	0.99	7.40	0.009
Young bucks	61.6	1.10	8.11	0.009
Young does	39.0	0.67	5.19	0.006
Weaners	26.0.	0.45	3.66	0.004
Kids	16.0	0.29	2.54	0.003

MEF: methane emission factor; kg/h/year: kg/head/year.

Table 3.10 Estimated methane emissions of meat type goats in South Africa according to provinces, based on 2010 population figures (Gg/year)

	Commercial goats			Communal goats		
Province	Population	Enteric methane (Gg)	Manure methane (Gg)	Population	Enteric methane (Gg)	Manure methane (Gg)
Western Cape	61467	0.53	5.6x10-4	151718	0.83	4.5x10-4
Eastern Cape	643295	5.51	5.9x10-3	1587977	8.57	4.6x10-3
Northern Cape	143953	1.26	1.3x10-3	355356	2.0	1.1x10-3
KwaZulu-Natal	227269	1.94	2.1x10-3	561018	3.0	1.6x10-3
Free State	66653	0.58	6.4x10-4	164529	0.91	4.9x10-4
North West	201583	1.75	1.9x10-3	497623	2.74	1.5x10-3
Gauteng	10924	0.09	9.9x10-5	26972	0.14	7.83x10-5
Mpumalanga	24580	0.21	2.2x10-4	60687	0.32	1.8x10-4
Limpopo	348820	3.0	3.3x10-3	861081	4.23	2.3x10-3
Total	1728544	14.9	1.6x10-2	4266961	22.7	1.2x10-2

In 2010 the Eastern Cape province had the largest goat population, accounting for 37% of the national flock, followed by Limpopo, KwaZulu-Natal and North West with 20%, 13% and

11%, respectively. The remaining five provinces accounted for 30% of the national flock (DAFF, 2011). The provincial methane emissions of South African meat goats for 2010 are reported in Table 3.10. Eastern Cape represented 37.4% of the methane emissions originating from meat goats, which corresponds with the population data reported earlier (DAFF, 2011). The emerging/communal sector was responsible for 60.5% of the methane emissions generated from meat goats nationally, and accounted for 71% of the total national meat goat flock.

The majority of countries calculated goat emission factors for inventory purposes on a Tier 1 level according to the IPCC (2006) guidelines using IPCC default factors. The default factors adopted by the IPCC for goats are based on the work of Crutzen *et al*. (1986), who calculated the methane emission factor for goats from research by Panday (1981) in India on goats with a gross energy intake of 14 MJ per day. The average gross energy intake for commercial sheep in this study was 25.8 MJ/day, assuming a gross energy concentration of 18.4 MJ/kg DM (SCA, 1990). Gross energy intake of emerging/communal sheep was calculated as 15.5 MJ/day, yielding a herd average methane emission factor of 6.33 kg CH_4/head/year compared with the IPCC default factor of 5 kg CH_4/head/year.

Enteric methane emission factors from other developing countries are summarized in Table 3.11. The emission factors for India were sourced from experimental data (Singh and Mohini, 1996); emission factors from Thailand and China were sourced from country-specific figures based on IPCC guidelines (Dong *et al*., 2000; Yamaji *et al*., 2003) and Japanese figures are based on direct and indirect measurement techniques (Shibata *et al*., 1993).

Table 3.11 Methane emission factors for goats in developing countries and IPCC default values

Country	Enteric CH_4 emission factor (kg/head/year)	Manure CH_4 emission factor (kg/head/year)	Reference
South Africa: Commercial (2010)	10.1	0.032	Table 3.5: Present estimation
South Africa: Communal (2010)	6.33	0.007	Table 3.6: Present estimation
South Africa: Commercial (2004)	5.0	0.20	Otter, (2010)
South Africa: Communal (2004)	5.0	0.17	Otter, (2010)
IPCC: Developed countries	5.0	0.20	IPCC (2006)
IPCC: Developing countries	5.0	0.17	IPCC (2006)
Brazil	5.0		Lima *et al*. (2002)
India	3.9		Singh and Mohini (1996)
Thailand	5.0		Yamaji *et al*. (2003)
China: Breedable	7.1		Dong *et al*. (2000)
China: Other	3.6		Dong *et al*. (2000)
Japan	4.1		Shibata *et al*. (1993)

The enteric methane emissions from South African commercial and communal goats are higher than the IPCC default values and those of other developing countries (Table 3.11). The goat emission factors from other developing countries are based on animals that are smaller than South African goats with lower DM intakes (Crutzen *et al*. 1986; Singh and Mohini, 1996; Yamaji *et al*. 2003). Their estimated goat emission factors, however, are comparable with sheep emission factors reported earlier with commercial animals producing 0.42 and 0.40 g CH_4/kg LW/day for goats and sheep (excluding Karakul sheep), respectively, and 0.37 and 0.40 g CH_4/kg LW/day for emerging/communal goats and sheep repectively in South Africa.

The estimated manure emission factors reported in Tables 8 and 9 are considerably lower than manure emission factors reported in Table 3.11 from international sources and the IPCC (2006) default values. These differences could be owing to the use of country-specific manure emission data according to Gonzalez-Avalos and Ruiz-Suarez (2001) and the Australian National Inventory Report (2009) methodology, which differ from the IPCC default manure emission factors.

Angora

Mohair South Africa (2011) estimated the national Angora goat population at 1 million. Angora goats are farmed with mainly for the production of mohair in three provinces, Eastern Cape, Western Cape and Northern Cape, with 72%, 27% and 1% of the population, respectively (Roets, 2004; Mohair South Africa, 2011). The methane emission factors for Angora goats are reported in Table 3.12. Breeding bucks had the highest total methane emission factors with 6.01 kg CH_4/head/year, but the lowest emissions per kg DM intake of 20.6 g CH_4/kg DMI, with Angora kids producing 24 g CH_4/kg DMI. Breeding does and young Angora goats produced 21.4 and 21.7 g CH_4/kg DMI/day. The average MEF for Angora goats across all classes was 4.2 kg CH_4/head/year, which is low compared with commercial and emerging/communal meat goat emissions of 10.1 and 6.33 kg CH_4/head/year, respectively, but the average daily methane production per kg dry matter intake was slightly higher.

Table 3.12 Estimated methane emission factors for South African Angora goats

Animal class	Weight (kg)	Intake (kg/ day)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)	Daily enteric CH_4 (g/kg DMI)
Breeding bucks	41.5	0.80	6.01	0.0062	20.6
Breeding does	30.0	0.61	4.76	0.005	21.4
Young bucks	29.5	0.57	4.51	0.004	21.7
Young does	22.5	0.46	3.64	0.003	21.7
Weaners	20.5	0.41	3.39	0.003	22.7
Kids	14.5	0.30	2.63	0.002	24.0

MEF: methane emission factor; kg/h/year: kg/head/year; DMI: dry matter intake.

Table 3.13 reports on the provincial methane emissions from Angora goats in South Africa in 2010. Angora goats contributed 2.9 Gg to the methane emissions in 2010, with Eastern Cape being the largest contributor with 97% or 2.8 Gg.

Table 3.13 Estimated methane emissions of South African Angora goats according to provinces, based on 2010 population figures (Gg/year)

Province[#]	Commercial goats		
	Population	Enteric methane (Gg)	Manure methane (Gg)
Western Cape	270000	$3.3x10^{-2}$	$1.01x10^{-3}$
Eastern Cape	720000	2.8	$2.7x10^{-3}$
Northern Cape	10000	$4x10^{-2}$	$3.84x10^{-5}$
Total	1000000	2.9	0.0037

Angora goats are commercially farmed with only in Western Cape, Eastern Cape and Northern Cape (Mohair South Africa, 2011)

Milk goats

The South African commercial milk goat industry is relatively small, with an estimated population of 21000 animals across all provinces, and a negligible methane emission contribution of 0.17 Gg per annum. Goats that are milked for personal consumption in emerging and communal production systems were incorporated in the emerging/communal meat goat population figures. The average methane emission factor for commercial milk goats in South Africa is 6.9 kg CH_4/head/year varying from 3.6 to 10.5 kg CH_4/head/year for kids to breeding bucks. Table 3.14 reports on the methane emission factors for milk goats in South Africa. The average weight and methane emission factor are comparable with those of emerging/communal meat goats, 45 kg vs. 46.5 kg and 6.9 kg CH_4/head/year vs. 6.3 kg CH_4/head/year, respectively.

Table 3.14 Live weight, intake and estimated methane emission factors for South African milk goats

Animal class	Weight (kg)	Intake (kg/day)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)
Breeding bucks	72.5	1.45	10.5	0.009
Breeding does	48.0	1.16	8.48	0.007
Young bucks	53.0	1.03	7.65	0.006
Young does	40.5	0.78	5.94	0.005
Weaners	33.5	0.65	5.02	0.004
Kids	22.5	0.44	3.62	0.003

MEF: Methane emissions factor; kg/h/year: kg/head/year.

The provincial methane emissions of South African commercial milk goats in 2010 are presented in Table 3.15. The Northern Cape and Western Cape provinces accounted for approximately 80% of the total methane emissions from milk goat production systems in South Africa.

Table 3.15 Estimated methane emissions of milk goats in South Africa according to provinces, based on 2010 population figures (Gg/year)

Province	Commercial milk goats		
	Population	Enteric methane (Gg)	Manure methane (Gg)
Western Cape	7329	0.047	$3.7x10^{-5}$
Eastern Cape	444	0.0029	$2.24x10^{-6}$
Northern Cape	9296	0.061	$4.74x10^{-5}$
KwaZulu-Natal	1162	0.0075	$5.85x10^{-6}$
Free State	1119	0.0073	$5.69x10^{-6}$
North West	598	0.0039	$3.03x10^{-6}$
Gauteng	444	0.0029	$2.2x10^{-6}$
Mpumalanga	58	0.0004	$2.97x10^{-7}$
Limpopo	387	0.04	$1.96x10^{-6}$
Total	20837	0.172	$1.1x10^{-4}$

The methane emission factor reported in Table 3.14 for breeding does (8.48 kg CH_4/head/year) is higher than emissions reported by Singh and Mohini (1996) of 4.99 kg CH_4/head/year for milking goats older than a year. Milk goat breeding does had the highest methane emission (g CH_4/kg LW) across all adult goat breeds, producing 0.48 g CH_4/kg LW in South Africa. This is probably owing to the higher DMD of diets fed to breeding and lactating milk goat does. Pelchen and Peters (1998) reported a rise in sheep methane emissions (g/day) with an increase in digestibility of rations up to approximately 72% DMD, with a significant decrease in methane emissions if diet DMD was increased above 72%.

Karakul sheep and Angora goats apparently are the least efficient small stock breeds in terms of daily methane production, producing the highest enteric methane emissions per kg DM intake for both South African sheep and goat breeds. Commercial dual purpose sheep apparently are the lowest methane emitters per kg DM intake at 20.5 g CH_4 /kg DMI/day. Table 3.16 reports on the calculated daily enteric methane production per kg DM intake of small stock in South Africa.

Table 3.16 Estimated daily enteric methane production per kg DM intake of South African small stock breeds

Small stock	Breed	Commercial CH_4 production	Communal CH_4 production
Sheep	Merino	20.7	21.3
	Other wool	20.5	21.0
	Non wool	20.6	21.2
	Karakul	20.9	21.7
Goats	Meat goats	19.8	20.7
	Angora	21.5	
	Milk	20.5	

The variation among breed types within production systems is very small, as shown in Table 3.15. Meat goats produced the least amount of enteric methane per kg DM intake in both commercial and emerging/communal production systems with Karakul sheep the highest enteric methane contributors per kg DM intake in both systems.

Conclusion

Small stock is a major source of methane emissions in the South African agricultural sector. A detailed, updated methane emissions inventory on a provincial basis was developed using improved country specific emission factors based on the IPCC good practice guidelines. The sheep industry contributed an estimated 167 Gg of methane in 2010, and the goat industry 40.7 Gg, with a combined 15.6% of South Africa's total livestock methane emissions in 2010. The commercial sheep industry contributed an estimated 91% of sheep emissions, whereas 56% of goat methane emissions originated from the emerging/communal sector. Previous inventories underestimated the emissions contribution from small stock as the IPCC default values for African countries are not representative of South African sheep and goat production systems. Neither South African sheep nor goat commercial or communal emission factors were comparable with other developing and developed countries. The differences between the current inventory and previous inventories using default Tier 1 emission factors is between 20% and 70% for sheep and 25% and 100% for goat emissions. Efforts have been made to reduce uncertainties in activity data, but uncertainties will remain as no emission measurements exist for South Africa. It is important to conduct emission studies on enteric fermentation and manure management for small stock in all provinces and on all types of small stock to produce accurate baseline figures, which is critical to future mitigation protocols.

Acknowledgements

This work is based on the research supported wholly by the National Research Foundation of South Africa and the RMRD SA.

References

AFRC. 1990. Nutritive requirements of ruminant animals: energy. AFRC technical committee on responses to nutrients, report no 5. Agricultural and Food Research Council. Nutr. Abstr. Rev. Series B 60, 729-804.

Afrino Breeders' Society of South Africa, 2011. Report to authors on live weight of animals. www.afrino.co.za

Alemu, A.W., Dijkstra, J., Bannik, A., France, J. and Kebreab, E., 2011. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. Anim. Feed Sci. Technol. 166, 761-778.

ARC. 1980. The Nutrient Requirements of Ruminant Livestock, Technical Review. Agricultural Research Council. CAB. Slough, UK.

Archibeque, S., Haugen-Kozyra, K., Johnson, K., Kebreab, E. and Powers-Schilling, W., 2012. Near term options for reducing greenhouse gas emissions from livestock systems in the United States beef, dairy and swine production systems. Eds: Olander, L.P. and Van de Bogert, A., Nicholas Institute of Environmental Policy Solutions, Report 12-04, July 2012.

ANIR, 2009. Australian National Inventory Report - Australian National Greenhouse Accounts: National Inventory Report. Department of Climate Change and Energy Efficiency, Commonwealth of Australia, Canberra, ACT.

Blignaut, J.N., Chitiga-Mabugu, M.R. and Mabugu, R.M., 2005. Constructing a greenhouse gas inventory using energy balances: The case of South Africa 1998. J. Energy S. Afr. 16, 21-32.

Boerbok South Africa, 2011. Report to authors on the Boerbok live weights and flock structure. www.boerboksa.co.za

Crutzen, P.J., Aselmann, I. and Seiler, W., 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. Tellus 38B, 271-284.

De Waal, H.O., 1990. Animal production from native pasture (veld) in the Free State region – A perspective of the grazing ruminant. S. Afr. J. Anim. Sci. 20, 1-9.

DAFF, 2010. Department of Agriculture, Forestry and Fisheries - Livestock population statistics 2010. Pretoria, South Africa.

DAFF, 2011. Department of Agriculture, Forestry and Fisheries - A profile of the South African market value chain, 2011. Directorate Marketing, Arcadia, Pretoria, South Africa.

DEAT, 2009. Department of Environmental Affairs and Tourism - Greenhouse gas inventory, South Africa.
Communication under the United Nation Framework Convention on Climate Change. Pretoria, South Africa.

Döhne Merino Breed Society of South Africa, 2011. Report to authors on animal live weight.

www.dohnemerino.org

Dong, H., He, Q., Li, Y. and Toa, X., 2000. Livestock production and CH_4 emission from enteric fermentation of domestic livestock in China. In: Proceedings of the IGES and NIES workshop on GHG inventories for Asian Pacific region, Hayama. pp. 50-60.

Dorper Sheep Breeders' Society of South Africa, 2011. Report to authors on animal live weight. www.dorpersa.co.za

Dugmore, T.J. and Du Toit, J.H., 1988. The chemical and nutritive value of kikuyu pasture. S. Afr. J. Anim. Sci. 18, 2.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2012. The carbon and water footprint of the South African livestock industry. RMRD SA Project: Progress report. www.RMRDSA.co.za

FAO, 2006. Food and Agriculture Organization of the United Nations, 2010. [Accessed on 5 March 2012] FAOSTAT.

Gonzalez-Avalos, E. and Ruiz-Suarez, L.G., 2001. Methane emission factors from cattle manure in Mexico. Biosecure Technol. 80 (1), 63-71.
Howden, S.M. and Reyenga, P.J., 1987. Methane emissions from Australian livestock: Implication of the Kyoto protocol. Aust. J. Agric. Res. 50, 1285-1291.

IPCC, 2000. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483-2492.

Karakul Club, 2011. Report to authors on live weight of animals. Karakoel Str, Upington, 8801, South Africa.

Kebreab, E., Clark, K., Wagner-Riddle, C. and France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci. 86, 135-158.

Lassey, K.R., 2007. Livestock methane emission: From the individual grazing animal through national inventories to the global methane cycle. Agric. Forest Meteorology 142, 120-132.

Lima, M.A., Young Pessoa, M.C.P. and Vieira Ligo, M.A., 2002. First Brazilian inventory of anthropogenic greenhouse gas emissions, background reports: Methane emissions from livestock. Ministry of Science and Technology, Brazil.

Masika, P.J., Mafu, J.V., Goqwana, M.W., Mbuti, C. and Raats, J., 1998. A comparison of goat growth performance in a communal and commercial farming system in the Central

Eastern Cape Province, South Africa. In: Proceedings of Research and training strategies for goat production systems in South Africa. Eds. Webb, E.C., Cornje, P.B. and Donkin, E.F., Hogsback, Eastern Cape, South Africa. pp. 34 – 41.

Meissner, H.H., Hofmeyr, H.S., Van Rensburg, W.J.J. and Pienaar, J.P., 1983. Classification of livestock for realistic prediction of substitution values in term of a biologically defined large stock unit. Technical Communication, Department of Agriculture, Republic of South Africa.

Merino Breeders Society of South Africa, 2011. Report to authors on animal live weight. www.merinosa.co.za

Mills, J.A., Dijkstra, J., Bannik, A., Cammell, S.B., Krebreab, E. and France, J., 2001. A mechanistic model of whole tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation and application. J. Anim. Sci. 79, 1584-1597.

Minson, D.J. and McDonald, C.K., 1987. Estimating forage intake from growth of cattle. Trop. Grassl. 21 (3), 116-121.

Mohair South Africa, 2010. Report to authors on goat numbers in South Africa. Mohair SA, Port Elizabeth.

Mohair South Africa, 2011. Report to authors on live weight and production data. Mohair SA, Port Elizabeth.

Muller, C.J.C., 2005. Genetic parameter estimation and breeding plans for the South African dairy goat herd. PhD thesis, University of Stellenbosch, South Africa.

National Wool Growers' Association, 2011. Report to authors on sheep numbers and flock structures in South Africa.
New Zealand Greenhouse Gas National Inventory Report, 2010. Agricultural sector 1990 - 2010: A Pickering and S Wear, Ministry of Agriculture and forestry, Ministry of the environment, New Zealand.
http://www.mte.govt.nz/publications/climate/greenhouse_gas_inventrory/2012/index.html

O'Reagain, P.J. and Owen-Smith, R.N., 1996. Effects of species composition and sward structure on dietary quality in cattle and sheep grazing South African sourveld. J. Agric. Sci. 127, 261-270.

Otter, L., 2010. The South African agricultural GHG inventory for 2004. Department of Agriculture, Forestry and Fisheries, South Africa.

Panday, A.N., 1981. Vegetation and bovine population interactions in the savannah grazing lands of Chandraprabha sanctuary, Varansi. II. Seasonal behaviour of grazing animals and an assessment of carrying capacity of the grazing lands. Trop. Ecol. 22, 170-186.

Pelchen, A. and Peters, K.J., 1998. Methane emissions from sheep. Small Rumin. Res. 27, 137-150.

Penttilä, A., Slade, E.M., Simojoki, A., Riutta, T., Minkkinen, K. and Roslin, T., 2013. Quantifying beetle-mediated effects on gas fluxes from dung pats. PloS One 8 (8), 1 – 7.

Roets, M., 2004. From folklore to feasibility: Commercialisation of South Africa's indigenous goats. PhD thesis. University of Pretoria, South Afica.

Sallaku, E., Vorpsi, V., Jojic, E., Sallaku, F. and Dodona, E., 2011. Evaluation of methane emissions from animal farms in Shkodra district - Albania. Res. J. Agric. Sci. 43 (3), 484-492.

SCA, 1990. Standing Committee on Agriculture - 'Feeding standards for Australian livestock, Ruminants', CSIRO Publications, Australia.

Scholtz, M.M., Steyn, Y., Van Marle-Köster, E. and Theron, H.E., 2012. Improved production efficiency in cattle to reduce their carbon footprint for beef production. S. Afr. J. Anim. Sci. 42, 450-453.

Shibata, M., Terada, F., Kurihara, M., Nishida, T. and Iwasaki, K., 1993. Estimation of methane production in ruminants. Anim. Sci. Technol. (Japan) 64 (8), 790-796.

Singh, G.P. and Mohini, M., 1996. Methane production by Indian ruminant livestock. Curr. Sci. 71 (7),
580-582.

Smith, B., 2006. Natural resources. In: The Farming Handbook. University of KwaZulu-Natal Press. South Africa.

South African Milch Goat Breeders' Society, 2012. Report to authors on milk goat population and production data.

South African Mutton Merino Breeders' Society, 2011. Report to authors on animal live weights. www.savleismerino.net.

Statistics South Africa: Abstract of Agricultural Statistics, 2010. Directorate: Agriculture Statistics, DAFF, Pretoria, South Africa.

Swammy, M. and Bhattacharya, S., 2006. Budgeting anthropogenic greenhouse gas emission from Indian livestock using country specific emission coefficients. Curr. Sci. 91 (10), 1340-1354.

Tainton, N.M., 1981. Veld Management in South Africa. Chapter 2: The ecology of the main grazing lands of South Africa. Pietermaritzburg: University of Natal Press.

Tainton, N.M., 1999. Veld Management in South Africa. Chapter 2: The ecology of the main grazing lands of South Africa. Pietermaritzburg: University of Natal Press, South Africa.

Yamaji, K., Ohara, T. and Akimoto, H., 2003. A country-specific, high resolution emission inventory for methane from livestock in Asia in 2000. Atmospheric Environ, 37, 4393-4406.

Appendix 3A

Table 3A.1 Ratio of veld types per province (Tainton, 1981; 1999)

	Sweetveld	Sourveld	Mixed veld
Western Cape	0.5	0.3	0.2
Northern Cape	1.0	0	0
Eastern Cape	0.35	0.35	0.3
Free State	0.8	0.1	0.1
KwaZulu-Natal	0.2	0.6	0.2
Mpumalanga	0.15	0.7	0.15
Limpopo	0.6	0.2	0.2
Gauteng	0.2	0.6	0.2
North West	0.7	0.25	0.05

Table 3A.2 Veld digestibilities (Dugmore and Du Toit, 1988; De Waal, 1990; O'Reagain and Owen-Smith, 1996)

	Sweetveld	Sourveld	Mixed veld
Spring	65	65	65
Summer	60	60	60
Autumn	55	50	50
Winter	50	45	45

Appendix 3B

Table 3B.1 Live weights of commercial sheep breeds (NWGA, 2011 and Breed associations)

Animal class	Merino weight (kg)	Other wool weight (kg)	Non wool weight (kg)	Karakul weight (kg)
Breeding ram	97.5	137.5	97.5	72.5
Breeding ewe	53.0	68.0	63.25	48.0
Young ram	78.4	98.3	68.3	53.0
Young ewe	42.5	55.5	47.5	40.5
Weaners	37.5	31.5	37.5	33.5
Lambs	22.5	22.5	22.5	22.5

Table 3B.2 Live weights of communal sheep breeds

Animal class	Merino weight (kg)	Other wool weight (kg)	Non wool weight (kg)	Karakul weight (kg)
Breeding rams	78.0	110.1	78.1	58.0
Breeding ewes	42.1	54.5	50.3	38.4
Young rams	62.6	59.5	54.3	42.4
Young ewes	34.0	44.0	38.0	32.4
Weaners	30.0	25.0	30.0	26.8
Lambs	18.0	18.0	18.0	18.0

Table 3B.3 Proportion breeding ewes per season (lambing seasons) per province – commercial sheep

Province	Spring %	Summer %	Autumn %	Winter %
Western Cape				100
Northern Cape			100	
Eastern Cape	20		80	
Free State	20		80	
KwaZulu-Natal	20		80	
Mpumalanga	20		80	
Limpopo	20		80	
Gauteng	20		80	
North West	20		80	

Table 3B.4 Proportion breeding ewes per season (lambing seasons) per province – communal sheep

Province	Spring %	Summer %	Autumn %	Winter %
Western Cape	25	25	25	25
Northern Cape	25	25	25	25
Eastern Cape	25	25	25	25
Free State	25	25	25	25
KwaZulu-Natal	25	25	25	25
Mpumalanga	25	25	25	25
Limpopo	25	25	25	25
Gauteng	25	25	25	25
North West	25	25	25	25

Appendix 3C

Table 3C.1 Mean live weights for commercial meat goats

Animal class	Weight (kg)	$MEF_{enteric}$ (kg/h/year)	MEF_{manure} (kg/h/year)
Breeding bucks	118	18.3	0.02
Breeding does	78.0	12.1	0.013
Young bucks	88.3	13.1	0.014
Young does	55.5	8.0	0.0084
Weaners	37.5	5.5	0.006
Kids	22.5	3.6	0.0034

MEF: Methane emissions factor; kg/h/year: kg/head/year.

Table 3C.2 Mean live weights for communal meat goats

Animal class	Weight (kg)
Breeding bucks	82
Breeding does	54.4
Young bucks	61.6
Young does	39
Weaners	26
Kids	16

Table 3C.3 Mean live weights of Angora goats

Animal class	Weight (kg)
Breeding bucks	41.5
Breeding does	30.0
Young bucks	29.5
Young does	22.5
Weaners	20.5
Kids	14.5

Table 3C.4 Mean live weights of South African milk goats

Animal class	Weight (kg)
Breeding bucks	72.5
Breeding does	48.0
Young bucks	53.0
Young does	40.5
Weaners	33.5
Kids	22.5

Chapter 4

Direct greenhouse gas emissions of the game industry in South Africa

C.J.L. du Toit[1,3,#], H.H Meissner[2] and W.A. van Niekerk[3]
[1]Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria,0001, South Africa
[2]189 van Riebeeck Avenue, Lyttelton Manor, Centurion, 0157, South Africa
[3]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa

Abstract
Previous greenhouse gas (GHG) inventories did not include game as an emissions source. Recently game farming has become a recognized commercial enterprise in the agricultural sector in South Africa, contributing approximately R10 billion to the sectorial gross domestic product. The objective of this study was to estimate methane (CH_4) and nitrous oxide (N_2O) emissions from privately owned game animals based on international recognized methodologies. The emissions were calculated on the basis of a large stock unit (LSU) selecting different quality diets. Daily enteric methane emissions were estimated as 0.28, 0.22, and 0.18 kg CH_4/LSU/day consuming diets of 55%, 65% and 75% digestibility, respectively. The game industry contributed an estimated 131.9 Giga grams (Gg) of methane annually to agricultural emissions with the provinces of Limpopo, Eastern Cape and Northern Cape being the three largest contributors with 43.4, 37.3 and 21 Gg methane, respectively. The total privately owned game population was estimated at 2991370 animals, utilizing 20.5 million hectares.

Keywords: methane, nitrous oxide, wildlife, emission factors
[#]Corresponding author: dutoitcjl@tut.ac.za

Introduction

Game or wild ungulates have always inhabited southern Africa, although the population size has fluctuated greatly over the past 100 years. The establishment and growth of the private game industry is largely responsible for an increase in the number of game in recent years (Eloff, 2002; Bothma and Van Rooyen, 2005). Similarly, the industry has shown a steady growth in the number of game farms from 2280 in 1980 to 9000 in 1992 (Nell, 2003) and approximately 10000 currently (G. Dry, 2013, Pers. Comm., Wildlife Ranching South Africa, P.O. Box 23073, Gezina, 0031, South Africa). The private game ranching industry occupies 16.8% (20 500000 ha) of South Africa's total land area. This figure equates to 24% of South Africa's 84 million hectares of grazing land (Dry, 2011). This is more than double the area of officially declared conservation areas and approximately fivefold the area of the national parks (Carruthers, 2004).

Game farming or ranching has become an organized and recognized enterprise in the agricultural industry (Eloff, 1996; Van Der Waal and Dekker, 2000). According to a recent article by Van Rooyen (2013) the wildlife industry ranked fifth largest in the agricultural sector, contributing R10 billion to the country's gross domestic product (GDP). Game farming is defined as an agricultural system in which wild animals are maintained in order to harvest by-

products such as meat and skins in a domesticated or semi-domesticated manner by being enclosed in relatively small areas and provided with regular supplementary feeding and water (Carruthers, 2004; Du Toit, 2007). Part of the success of the industry is the ability of game to produce higher returns, compared to conventional livestock farming, under particular circumstances that may enhance the utilization of land with low agricultural potential (ABSA, 2003).

Herbivorous game, with the exception of elephant, rhinoceros, hippopotamus, zebra, warthogs and bushpigs, are ruminants. Ruminants contribute to greenhouse gas (GHG) emissions through methane emissions directly from digestive processes and methane (CH_4) and nitrous oxide (N_2O) emissions originating from manure. The quantity of CH_4 produced by ruminants is influenced by the level of intake, composition of the diet, and level of production of the animal. Game species select for diet quality in accordance with their feeding habits, and were classified by Hofmann (1973) as bulk and roughage eaters (grazers), selectors of concentrated herbage (browsers) and intermediate feeders (grazing and browsing). These three groups typically select diets with an approximate digestibility of 55%, 75% and 65%, respectively (Meissner *et al.*, 1983). These differences in diet quality influence energy intake as well as the amount of gross energy intake, which is lost as methane and thus methane emissions.

Game is considered a source of anthropogenic emissions. Previous GHG inventories for the livestock sector in South Africa did not include privately owned game as an emission source. The game industry has developed into a commercial farming sector, and emissions from all such sectors in the livestock industry need to be included in order to provide a complete and representative emissions inventory of the livestock sector. The aim of this study was to calculate methane emissions originating from privately owned game.

Methodology

Various sources have reported on the privately owned game population, which have varied from as low as 1.7 million (Van der Merwe and Saayman, 2003), to 2.5 million (G. Dry, 2013, Pers. Comm., Wildlife Ranching South Africa, P.O. Box 23073, Gezina, 0031, South Africa), to 9 million (NAMC, 2006), to 16 million (Van Rooyen, 2013), to as high as 18.6 million (ABSA, 2008). The majority of sources agreed on the surface area under private game nationally of 20.5 million hectares (NAMC, 2006; ABSA, 2008; Cousins *et al.*, 2008, Dry, 2011). Owing to the large variations in literature quotes of the number of privately owned game in South Africa, game emissions were calculated according to the grazing capacity of an area on a provincial basis in terms of large stock units (LSU) and were not based on individual population figures.

The calculations followed the principles of the IPCC (2006) guidelines. Grazing capacity is defined as the area of land required to maintain a single LSU over an extended number of years without deterioration of the vegetation or soil. It was assumed that wildlife farmers stock their farms according to the ecological carrying capacity of the farm. Table 4.1 indicates the number of exempted game farms in South Africa, based on data from 2000, according to Eloff (2002) and Van der Merwe and Saayman (2003).

Table 4.1 Proportion of exempted game farms in South Africa (Eloff, 2002; Van der Merwe and Saayman, 2003)

Province (year 2000)	% of game farms	% of game farms according to hectares
Free State	3.56	1.43
Limpopo	49.0	32.1
North West	6.72	3.51
Mpumalanga	4.05	2.66
Gauteng	1.42	0.79
KwaZulu-Natal	1.78	1.63
Eastern Cape	12.3	8.51
Northern Cape	19.5	46.8
Western Cape	1.62	2.56
Total	100	100

Similar ratios on the percentage of game farms per province have been reported by ABSA (2008) and Dry (2011), although the total surface area of the game farms has increased from 10.4 million hectares in 2000 (Eloff, 2002) to 20.5 million hectares currently (Dry, 2011).The estimation of the surface area of private game farms per province was based on the ratio reported in Table 4.1 and the national total of 20.5 million hectares. The emissions calculations in this study were based on surface area under game farms incorporating carrying capacity of regions, owing to the uncertainty in game population numbers.

Provinces in South Africa were divided into five ecological regions, namely Grassland, Lowveld, Bushveld, Kalahari and Karoo, according to Bredenkamp *et al.* (1996). Grassland is defined as the higher inner plateau with an annual rainfall of between 500 mm and 800 mm, dominated by various grass types with limited trees and shrubs. The Lowveld, Bushveld and Kalahari regions are grouped as savannah areas. The Lowveld region covers low-lying areas east of the Northern Drakensberg escarpment with an annual rainfall of between 400 mm and 600 mm. The Bushveld region refers to the northern parts of South Africa, west of the Drakensberg escarpment, including the Limpopo valley, with an annual rainfall of between 300 mm and 600 mm. The Kalahari region is classified as arid savannah, with an annual rainfall of between 200 mm and 400 mm per annum. The western part of the Karoo region is classified as semi-desert with an annual rainfall of less than 200 mm (Bredenkamp *et al.*, 1996; ABSA, 2003). The ecological carrying capacity (ha/LSU) of these regions was reported by ABSA (2003) as 4, 12, 15, 30, and 55 for Grassland, Lowveld, Bushveld, Kalahari and Karoo regions, respectively. The average farm size was estimated according to data reported by Van der Merwe and Saayman (2003). The area per ecological region per province is reported in Table 4.2.

Table 4.2 Average game farm size and surface area of ecological regions per province in South Africa

Province	Total area (ha) ('000)	Ave farm size (ha)	Surface area/ ecological region/ province				
			Grassland (ha)	Lowveld (ha)	Bushveld (ha)	Kalahari (ha)	Karoo (ha)
Free State	287	821	206066			18942	61992
Limpopo	6581	1340	210576	921270	5461815	6581	
North West	718	1073	208075		157850	351575	
Mpumalanga	554	1346	354240	132840	66420		
Gauteng	164	1140	127104		36900		
KZN	328	1876	118080	101680	108240		
Eastern Cape	1743	1413	702809		476284		563409
Northern Cape	9594	4921	32620			2830230	6732110
Western Cape	533	3234	5330		26650		501020

KZN: KwaZulu-Natal.

It was assumed that approximately 30% of the farms per province are larger than the average farm size according to research by Van der Waal and Dekker (2000). The habitat and size of the farm influence the minimum herd size and relative species distribution of a game farm (Appendix 4A and 4B). The total LSUs according to the ecological carrying capacity on a provincial basis are given in Table 4.3. A LSU is defined as a steer of 450 kg, which gains 500g/day on a pasture with a mean digestibility (DE) of 55% (Meissner *et al.*, 1983). The proportion of grazers, browsers and mixed feeders as a percentage of total large stock units per ecological region is reported in Table 4.4. The relative distribution of animal species on private game farms is different from that of national parks in South Africa (ABSA, 2003) and varies according to the size of the farm. The relative distributions of animal species and herd size per ecological region for small and large farms are reported in Appendices 1A and 1B.

Enteric methane emissions originating from game were calculated based on dry matter intake (I), (kg DM/head/day). The daily intake of animal types was calculated based on metabolizable energy requirements (MJ/day) of large stock units according to Meissner *et al.* (1983). The daily metabolizable energy (ME) requirements (MJ/day) of animals selecting diets with various levels of digestible energy concentrations were based on the net energy requirements of an LSU and the efficiency coefficients of ME utilization at a certain level of production, according to Meissner *et al.* (1983). Daily intake per animal type was calculated by dividing the ME requirement (MJ/day) by the ME concentration (MJ/ kg) of the selected diet.

Table 4.3 Distribution of large stock units per province according to ecological carrying capacity

Province	Large stock units		
	Large farm	Small farm	Total
Free State	15982	36946	52928
Gauteng	10271	23965	34236
Limpopo	148127	345631	493758
Mpumalanga	31217	72841	104058
KwaZulu-Natal	13563	32396	45959
Western Cape	3666	8554	12220
Northern Cape	67470	157429	224899
North West	22279	51982	74261
Eastern Cape	64803	334382	399185

Table 4.4 Animal types per ecological region as a percentage of large stock units (ABSA, 2003)

Animal type	Ecological region				
	Grassland	Lowveld	Bushveld	Kalahari	Karoo
Low selective grazers	20	25	20	10	2
High selective grazers	50	30	30	65	60
Mixed feeders	28	25	30	20	35
Browsers	2	20	20	5	3

Daily enteric methane (M), (kg/head/day) production was calculated according to Kurihara *et al.* (1999) based on emissions from cattle fed tropical grass species as:

$$M = (34.9 \times I - 30.8)/ 1000$$

Methane emissions from manure (M), (kg/ head/ day) of all game were calculated according to ANIR (2009) as:

$$M = I \times (1 - DMD) \times MEF$$

Where: I = dry matter intake (kg DM/head/day)
MEF = emissions factor (kg CH_4/ kg DM manure). The factor of 1.4 x 10^{-5} based on the work of Gonzalez-Avalos and Ruiz-Suarez (2001) was used.
DMD = diet digestibility (55% for grazers, 65% for browsers and 75% for concentrate selectors)

Game production systems are mainly extensive and manure is deposited directly on veld or rangeland. According to the IPCC (2006), N_2O emissions from manure deposited on rangeland or veld are reported under the managed soils section in the national inventory report format and not under livestock emissions. Nitrous oxide emissions originating from faeces and urine deposited on rangeland was calculated according to the ANIR (2009).

Results and Discussion

Game farming has become a recognized agricultural enterprise (Bothma, 1995; Eloff, 1996; Van der Waal and Dekker, 2000) but previous agricultural GHG inventories did not include game farming as an emission source (Blignaut *et al.*, 2005; Otter, 2010). The daily intake, estimated CH_4 emissions originating from enteric fermentation and manure, and estimated N_2O emissions from faecal matter deposited on soils from large stock units selecting various diets are presented in Table 4.5.

Table 4.5 Estimated daily intake, methane and nitrous oxide emissions of large stock units selecting different diet qualities

Animal class	Diet digestibility (%)	Intake (kg DM/day)	Enteric CH_4 (kg/head/day)	Manure CH_4 (kg/head/day)	Soil N_2O (kg/head/day)
Grazer	55	8.81	0.277	5.6×10^{-5}	5.4×10^{-4}
Intermediate feeders	65	7.08	0.216	3.5×10^{-5}	7.4×10^{-4}
Browsers	75	5.89	0.175	2.1×10^{-5}	1.07×10^{-3}

Every farm differs and has its own unique carrying capacity and game composition potential. The number of animals kept on a land unit is determined by the size of the habitat area, the carrying capacity of the unit, the social and spatial needs of the animals, as well as the interaction and composition of the animal species (Furstenburg, 2011). Domestic livestock have lost their natural social structure and territorial behaviour over the years, and carrying capacity is based on fodder production, consumption and veld type (Furstenburg, 2011). The carrying capacity on game farms incorporates animal social needs and habitat requirements. The use of grazing capacity as a base for the calculations is a source of uncertainty, as there is a difference between the grazing capacity of the veld and the stocking rate. Grazing capacity refers to the true number of animals the vegetation can sustain, and the stocking rate to the number of animals the farm manager perceives it can sustain (Smit, 2012). Smit (2012) stated that the use of LSU values for herbivorous game species does not allow for ecological separation, and overlooks the potential for using the specialized and complementary resource-use habits of wildlife to maximize veld utilization. The approach, however, is based on sound scientific principles and the error associated with an approach based on individual animal numbers will be larger owing to the large variation in reported game population numbers in South Africa.

The methane emissions of wildlife on private game farms per province are presented in Table 4.6. The game industry contributes an estimated 132 Gg in methane emissions per annum. These figures were calculated based on the average carrying capacity of game farms in each

province. Limpopo was the largest contributor in terms of methane emissions from farmed wildlife followed by Eastern Cape and Northern Cape, with 43.4 Gg (32.9%), 37.3 Gg (28.3%) and 21 Gg (15.9%) respectively of the total emissions. The emission calculations were based on LSUs as defined by Meissner *et al*. (1983). This may lead to a possible over-estimation of game emissions, as not all game animals are ruminants. Northern Cape has the largest surface area under private game farming (46.8%), followed by Limpopo (32.1%) and Eastern Cape (8.5%). The difference between provincial ranking according to surface area and methane emissions is because of the average carrying capacity of the provinces. Northern Cape has the largest surface area under private game farming, but it ranks only third in terms of methane emissions originating from private game. This is owing to the relatively low carrying capacity of the Karoo (55 ha/LSU), which covers approximately 70% of Northern Cape, compared to the carrying capacity of the Bushveld (15 ha/LSU) and Grassland (4ha/LSU) which cover approximately 86% and 68% of Limpopo and Eastern Cape, respectively.

The methane emissions per individual animal were calculated based on the energy requirements as described above. The calculated dry matter intake as a percentage of live weight is lower than that reported by Smit (2012) for game species. Meissner (1982) indicated that the feed intake of wild ungulates in subtropical regions is less than that of domestic livestock of comparable size. Curtzen*et al*. (1986) reported annual methane emissions of 34 kg, 50 kg, 5 kg, 26 kg, and 5 kg for buffalo, giraffe, impala, elephant and zebra, respectively. These estimates are considerably lower than those calculated in this study and reported in Table 4.7. The emission estimates reported by Curtzen *et al*. (1986) were based on animals with lower live weights and gross energy intakes than when compared with those reported in Table 4.7. The CH_4 emissions for elephant and zebra were based on emission values of horses, which have similar digestive systems, as 3.5% of digestible energy intake (Curtzen *et al*., 1986). The emissions from black wildebeest, tsessebe, blesbok, impala and springbok were based on the equation developed by Howden and Reyenga (1987) based on respiration chamber experiments on sheep in Australia. Warthog emissions were estimated according to the IPCC (2006) based on pigs in developing countries. All other methane emission estimates for game (giraffe, eland, buffalo, kudu, waterbuck and blue wildebeest) reported in Table 4.7 were based on an equation developed by Kurihara *et al*. (1999) based on cattle fed tropical pastures.

Table 4.6 Estimated methane emissions (Gg/year) and number of large stock units per animal class and province in South Africa

Province	Animal class	Large stock units	Enteric CH_4 (Gg/year)	Total CH_4 (Gg/year)	% contribution to total emissions
Free State	Grazers	37019	3.74		
	Mixed feeders	14824	1.17	4.98	3.78
	Browsers	1085	0.07		
Gauteng	Grazers	23473	2.37		
	Mixed feeders	9635	0.76	3.21	2.43
	Browsers	1128	0.07		
Limpopo	Grazers	261302	26.4		
	Mixed feeders	143214	11.3	43.4	32.9
	Browsers	89243	5.7		
Mpumalanga	Grazers	70295	7.11		
	Mixed feeders	28893	2.28	9.70	7.35
	Browsers	4871	0.31		
KwaZulu-Natal	Grazers	29457	2.98		
	Mixed feeders	12758	1.01	4.22	3.20
	Browsers	3743	0.24		
Western Cape	Grazers	7470	0.76		
	Mixed feeders	4095	0.32	1.12	0.85
	Browsers	655	0.04		
Northern Cape	Grazers	152354	15.4		
	Mixed feeders	63993	5.05	21	15.9
	Browsers	8552	0.55		
North West	Grazers	50464	5.10		
	Mixed feeders	20066	1.58	6.92	5.25
	Browsers	13738	0.24		
Eastern Cape	Grazers	272337	27.5		
	Mixed feeders	113110	8.92	37.3	28.3
	Browsers	126746	0.88		
Total		1441504	131.9	131.9	100

Giraffe and eland had comparable daily CH_4 emission factors (g CH_4/kg LW/day) to commercial beef bulls and cows with similar live weights (LW), according to Du Toit *et al.* (2013a), with 0.46 g CH_4/kg LW/day compared to 0.42 g CH_4/kg LW/day for giraffe and commercial bulls and 0.51 g CH_4/kg LW/day compared to 0.53 g CH_4/kg LW/day for eland and commercial beef cows, respectively. Buffalo had higher calculated daily CH_4 emission factors (0.67 g CH_4/kg LW/day) compared to commercial beef cows (0.53 g CH_4/kg LW/day) with similar live weights (Du Toit *et al.*, 2013a). The daily CH_4 emission factors of smaller antelope reported in Table 4.7 were compared to commercial small stock emission factors with similar live weights according to Du Toit *et al.* (2013b). Black wildebeest and tsessebe had estimated daily CH_4 emission factors (g CH_4/kg LW/day) that are similar to those of commercial dual purpose breeding rams, but lower emission factors than those of commercial breeding goat bucks with 0.39, 0.38, 0.37 and 0.43 for black wildebeest, tsessebe, commercial dual purpose breeding rams and breeding goat bucks, respectively. Impala and springbok had numerically higher estimated daily CH_4 emissions factors (g CH_4/kg LW/day) than commercially farmed goats with similar live weights as reported by Du Toit *et al.* (2013b) with 0.50 and 0.48 compared to 0.40 and 0.44 for impala, springbok, young does and kids, respectively.

Table 4.7 Approximate live weight (LW), large stock unit (LSU) substitution, diet digestibility, intake (% of live weight) and methane emissions of selected game species

Species	Weight (kg)[#]	LSU	Diet DE[*] (%)	Intake (%/LW)	CH_4 (kg/head/year)	CH_4 (g/kg LW/day)
Elephant	2436	3.83	55	1.4	81.0	0.10
Giraffe	826	1.51	65	1.4	136	0.46
Eland	528	1.08	65	1.6	93.7	0.51
Buffalo	466	1.08	55	2.1	113	0.67
Zebra	266	0.66	55	2.2	13.9	0.15
Kudu	155	0.44	65	2.2	31.3	0.56
Waterbuck	150	0.41	55	2.5	35.9	0.67
Blue wildebeest	153	0.43	75	1.8	24.8	0.44
Black wildebeest	106	0.30	75	1.9	14.3	0.39
Tsessebe	105	0.03	65	1.8	13.8	0.38
Blesbok	62	0.19	75	2.0	9.08	0.43
Warthog	59	0.21	75	2.4	2.22	0.18
Impala	42	0.15	75	2.4	7.40	0.50
Springbok	28	0.09	75	2.2	4.72	0.48

[#] Animal live weight and daily energy requirements used in intake calculations were sourced from Meissner *et al.* (1983).
* DE = feed digestibility

Tables 8a and 8b reports on the estimated South African privately owned game population according to province, based on the norms presented by ABSA (2003) in Appendix 4A and 4B. The total game population is estimated at 2991370 animals. This is in line with the figure reported by Dry (2011) of 2.5 million animals, but smaller than other figures reported in the literature (NAMC, 2006; ABSA, 2008: Van Rooyen, 2013).

Annual enteric methane emissions for individual game species reported in Appendix 4A.2 were calculated based on daily intake using the equations of Howden and Reyenga (1987), Kurihara *et al*. (1999), and the IPCC (2006), as discussed earlier. For hippopotamus and rhinoceros, the methane emissions were based on the daily methane emissions of elephant of 0.1 g CH_4/ kg LW/day. The live weights of game animals were sourced from Meissner *et al*. (1983) and Smit (2012). By basing the emission estimates on individual animal populations of approximately 3 million, the total methane emissions for the commercial game industry come to 59.9 Gg per year. This is considerably lower that the emission estimate based on LSUs and stocking rates of 132 Gg reported in Table 4.6. The variation in emission estimates is very large when game populations are used, 50.05 Gg from 2.5 million animals to 336.34 Gg from 18.6 million animals. The type of diet selected by game, the amount of methane produced per unit of feed intake, and variation in daily feed intake are further causes of uncertainty when emission estimates are based on animal populations.

Table 4.8a Estimated game numbers per province based on norms reported by ABSA (2003)

Animal Species		Provinces									
		Gt	Mpum	NC	NW	EC	Lim	FS	KZN	WC	Total
Low selective grazers											
LSU/animal											
1.07	Buffalo	288	2075	862	625	1732	12475	439	1299	26	19821
2.24	Hippo	7	49	0	28	84	1232	0	48	5	1453
2.75	White Rhino	112	335	181	224	674	1574	170	143	9	3422
0.66	Zebra (Burchell)	9418	27447	2249	17151	111990	124411	14206	11704	841	319418
0.66	Zebra (Cape mountain)	0	0	16073	1536	308	29	106	0	276	18328
High selective grazers											
LSU/animal											
0.22	Blesbok	14444	40255	3707	23645	26836	23929	26836	13759	606	174017
0.56	Gemsbok	20	36	72194	4165	3515	3003	470	58	2942	86403
0.37	Red hartebeest	4464	12273	37525	9814	11786	32248	8216	4588	1780	122694
0.25	Reedbuck	3325	9786	816	5833	7788	31718	5904	3968	240	69378
0.64	Roan	17	109	0	74	222	3100	0	110	12	3644
0.64	Sable	17	109	0	74	222	3100	0	110	12	3644
0.15	Springbok	21184	59040	274963	49914	51540	35382	41116	20180	11821	565140
0.38	Tsessebe	233	1468	0	998	2975	41769	0	1486	168	49097
0.5	Waterbuck	251	1581	0	1073	3203	44972	0	1600	181	52861
0.46	Wildebeest (black)	15543	43317	3989	25444	28878	25750	28878	14806	653	187258
0.5	Wildebeest (blue)	782	5593	80858	7917	13640	144896	527	5498	3844	263555

Gt: Gauteng; Mpum: Mpumalanga; NC: Northern Cape; NW: North West; EC: Eastern Cape; Lim: Limpopo; FS: Free State; KZN: KwaZulu-Natal; WC: Western Cape.

Table 4.8b Estimated game numbers per province based on norms reported by ABSA (2003)

Animal Species		Provinces									Total
		Gt	Mpum	NC	NW	EC	Lim	FS	KZN	WC	
Mixed feeders											
LSU/animal											
0.09	Duiker	2223	6660	19610	4888	7999	44604	3797	3146	1323	94250
1.08	Eland	7922	22061	46592	14226	18789	27678	14828	7795	3113	163004
5	Elephant	15	94	0	66	198	2754	0	96	11	3236
0.2	Impala	1292	9382	25000	8630	16486	240164	167	9190	933	311244
0.23	Nyala	0	1023	0	0	0	7093	0	783	0	8899
0.38	Ostrich	97	772	9857	940	1707	18525	64	742	490	33194
0.25	Reedbuck (mountain)	1156	3467	3595	2539	3114	17188	2006	1531	109	34705
0.25	Warthog	148	1594	9057	1756	1884	31080	61	1450	107	47137
Browse											
LSU/animal											
0.13	Bushbuck	114	954	0	486	1449	22001	0	907	82	25993
1.58	Giraffe	156	1072	269	699	1987	28537	2	1063	112	33897
0.07	Klipspringer	1160	3701	8108	2503	2954	15944	1736	1662	428	38196
0.54	Kudu	556	2386	8154	2407	4516	48619	933	1911	346	69828
0.13	Rhebuck (grey)	1800	5654	977	3314	3947	24798	2501	2527	153	45671
1.65	Rhino (Black)	9	56	129	54	114	1604	1	57	6	2030
0.06	Steenbuck	3371	10258	46959	6998	10842	49285	4680	4318	3245	139953
Total (a + b)		90124	272607	671724	198021	341379	1109462	157644	116533	33880	2991370

Gt: Gauteng; Mpum: Mpumalanga; NC: Northern Cape; NW: North West; EC: Eastern Cape; Lim: Limpopo; FS: Free State; KZN: KwaZulu-Natal; WC: Western Cape.

The CH_4 emissions estimates per species are reported in Appendix 4A.2. As CH_4 emissions originating from manure of game are very low, it is not reported in the table in Appendix 4A.2. Although the N_2O emitted from soil through the metabolism of manure and urine is not reported under livestock emissions according to the IPCC (2006) good practice guidelines, it is mentioned to provide a more complete scenario of emissions associated with game on privately owned land. Nitrogen in faecal matter is primarily in an organic form and must first be mineralized before it becomes a source of N_2O. The mineralization process occurs at significant rates in higher rainfall regions. However, the decay of faeces in drier areas is much slower,

with faeces remaining largely intact for months to years (ANIR, 2009). The N_2O emissions from faeces and urine voided in rangeland were estimated at 0.39 Gg N_2O/ year on a national scale using emission factors of 0.005 and 0.004 Gg N_2O-N/Gg N for faeces and urine, respectively, according to the ANIR (2009). Penttilä *et al.* (2013) reported that dung beetles could potentially increase GHG emissions from faeces voided on rangeland or veld, mainly due to increased N_2O emissions. The possible effect of dung beetles is noted but not included in the present inventory due to insufficient data under South African conditions. The Limpopo province had the largest emissions originating from game followed by Northern Cape and Eastern Cape provinces.

Conclusion

Game was not included in previous inventories, but was identified as a key CH_4 emissions source in the present inventory, contributing 132 Gg of CH_4. Nitrous oxide emissions from rangeland soils originating from faecal matter were estimated at 0.39 Gg N_2O/year. There is a great deal of uncertainty in the estimation of GHG emissions from game on game farms. To base the CH_4 emission estimation on the ecological carrying capacity of commercial game farms remains the soundest approach, as the variations in game population numbers and intake estimations are extremely large. Multiple sources agreed on the figure for the surface area under private game in South Africa of 20.5 million hectares and this appears the only justifiable basis for the emissions estimation.

Acknowledgement

This work is based on the research supported wholly by the National Research Foundation of South Africa and the RMRD SA.

References

ABSA, 2003. Game farm profitability in Southern Africa. The SA financial sector forum. Rivonia, South Africa.

ABSA, 2008. Game farm profitability in Southern Africa. The SA financial sector forum. Rivonia, South Africa.

ANIR, 2009. Australian National Inventory Report - Australian national greenhouse accounts: National inventory report. Department of climate change and energy efficiency, Commonwealth of Australia, Canberra, ACT.

Blignaut, J.N., Chitiga-Habugu, H.R. and Habugu, R.M., 2005.Constructing a GHG inventory using energy balances: The case of South Africa, 1998. J. Energy S. Afr. 16, 21-32.

Bothma, J.du P. and Van Rooyen, N., 2004. Using diet and plant resources to set wildlife stocking densities in African savannas. Wildlife Society bulletin, 32 (3), 840-841.

Bothma, J.du P., 1995. Introduction in: Game ranch management, 2nded. Ed. Bothma, J.du P., J.L. van Schaik, Hatfield, Pretoria, South Africa.

Bredenkamp, G., Granger, J.E. and Van Rooyen, N., 1996. Delimination of vegetation types. In: Vegetation of Southern Africa, Lesotho and Swaziland. Eds: Low, A.B. and Robelo, A.G., Department of Environmental Affairs and Tourism, Pretoria, South Africa.

Carruthers, J., 2004. "Wilding the farm or farming the wild"? The evolution of scientific game ranching in South Africa from the 1960s to the present. Trans. Royal Soc. S. Afr. 63 (2) 160-181.
Cousins, J.A., Sadler, J.P. and Evans, J., 2008.Exploring the role of private wildlife ranching as a conservation tool in South Africa: Stakeholder perspective. Ecology and Society 13 (2), 43-51.

Curtzen, P.J., Aselmann, I. and Seiler, W., 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. Tellus, 38B: 271-284.

Dry, G.C., 2011. Commercial wildlife ranching's contribution to a resource efficient. Low carbon, pro-employment green economy. Presentation at the 7th International Wildlife Ranching Symposium, Kimberley, October 2011. South Africa.

Du Toit, J.G., 2007. Report: Role of the private sector in the wildlife industry. Tshwane, Wildlife Ranching SA/Du Toit Wilddienste. 87 pp, South Africa.

Du Toit, C.J.L., Meissner, H.H. and Van Niekerk, W.A., 2013a. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43, 3.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013b. Direct greenhouse gas emissions of South African small stock sectors. S. Afr. J. Anim. Sci. 43, 3.

Eloff, T., 1996.Farming with the future. SA Game and Hunt. 2 (3), 21-24.

Eloff, T., 2002.The economic realities of the game industry in South Africa. In: Sustainable utilization in practice. Eds: Ebedes, H., Reilly, B., Van Hoven, W. and Penzhorn, B., Proceedings of the 5th International Wildlife Ranching Symposium, 2002. Pretoria, South Africa.

Furstenburg, D., 2011. Optimizing game production in a new era: The road to financial success. Agricultural Research Council: Range and Forage Institute, Grootfontein, Middelburg, South Africa. http://gadi.agric.za/articles/Furstenburg_D/optimizing-game-production.php?

Gonzalez-Avalos, E. and Ruiz-Suarez, L.G., 2001. Methane emission factors from cattle manure in Mexico. Biosecure Technology 80(1), 63-71.

Hofmann, R.R., 1973. The ruminant stomach. East African monographs. Biology 2, 1-354.

Howden, S.M. and Reyenga, P.J., 1987. Methane emissions from Australian livestock: Implication of the Kyoto protocol. Aust. J. Agric. Res. 50, 1285-1291.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

Kurihara, M., Magner, T., Hunter, R.A. and McCrabb, G.J., 1999.Methane production and energy partition of cattle in the tropics. Br. J. Nutr. 81, 227-234.

Meissner, H.H., 1982. Theory and application of a method to calculate forage intake of wild southern African ungulates for purpose of estimating carrying capacity. S. Afr. J. Wildl. Res. 12 (2), 41-47.
Meissner, H.H., Hofmeyr, H.S., Van Rensburg, W.J.J. and Pienaar, J.P., 1983. Classification of livestock for realistic prediction of substitution values in term of a biologically defined large stock unit. Technical communication, Department of Agriculture, Republic of South Africa.

NAMC (National Agricultural Marketing Council), 2006. Report on the investigation to identify problems for sustainable growth and development in South African wildlife ranching. Report No 2006-03, South Africa.

Nell, D.D'A., 2003. The development of wildlife utilization in South Africa and Kenya, 1950 – 1990. DPhil, thesis, University of Oxford, U.K.

Otter, L., 2010. The South African agricultural GHG inventory for 2004.Department of Agriculture, Forestry and Fisheries, South Africa.

Penttilä, A., Slade, E.M., Simojoki, A., Riutta, T., Minkkinen, K. and Roslin, T., 2013.Quantifying beetle-mediated effects on gas fluxes from dung pats. PloS One 8 (8), 1 – 7.

Smit, G.N., 2012. Grazing capacity - game. Calculation of grazing capacity and browse capacity for game species. Department of Animal, Wildlife and Grassland Sciences, University of the Free State, Bloemfontein, South Africa.

Van der Merwe, P. and Saayman, M., 2003. Determining the economic value of game farm tourism. Koedoe 46 (2), 103-112.

Van der Waal, C. and Dekker, B., 2000. Game ranching in the Northern Province of South Africa. S. Afr. J Wildl. Res. 30 (4), 151-156.

Van Rooyen, L., 2013. Game ranches unite to influence policy. Farmers Weekly, 9 April 2013, South Africa.

Appendix

Appendix 4A Minimum herd size and relative distribution of animal species per ecological region for larger farms (ABSA, 2003)

		Relative distribution of animal species as a % of LSU*				
Animal species	**Min. social herd size**	**Grassland**	**Lowveld**	**Bushveld**	**Kalahari**	**Karoo**
Low selective grazers		**20%**	**25%**	**20%**	**10%**	**2%**
Buffalo	**15**	**15**	**50**	**15**	**30**	
Hippo	**15**		**10**	**10**		
White Rhino	**5**	**15**	**10**	**15**	**15**	
Zebra (Burchell)	**5**	**70**	**30**	**60**		
Zebra (Cape mountain)	**10**				**55**	**100**
High selective grazers		**50%**	**30%**	**30%**	**65%**	**60%**
Blesbok	**12**	**20**				
Gemsbok	**12**			**5**	**30**	**30**
Red hartebeest	**12**	**10**		**5**	**10**	**10**
Reedbuck	**8**	**5**	**5**	**5**		
Roan	**12**		**5**	**5**		
Sable	**12**		**5**	**5**		
Springbok	**15**	**20**			**30**	**30**
Tsessebe	**12**		**5**	**5**		
Waterbuck	**12**		**10**	**10**		
Wildebeest (black)	**12**	**45**				
Wildebeest (blue)	**12**		**70**	**60**	**30**	**30**
Mixed feeders		**28%**	**25%**	**30%**	**20%**	**35%**
Duiker	**6**	**2**	**3**	**3**	**3**	**3**
Eland	**12**	**95**	**10**	**14**	**54**	**92**
Elephant	**12**		**40**	**35**		
Impala	**15**		**30**	**35**	**30**	
Nyala	**12**		**5**			
Ostrich	**6**		**4**	**5**	**5**	**5**
Reedbuck (mountain)	**8**	**3**	**3**	**3**	**3**	
Warthog	**12**		**5**	**5**	**5**	
Browsers		**2%**	**20%**	**20%**	**5%**	**3%**
Bushbuck	**8**		**3**	**3**		
Giraffe	**8**		**60**	**50**	**30**	
Klipspringer	**4**	**5**	**1**	**1**	**5**	**5**
Kudu	**12**	**80**	**20**	**30**	**40**	**90**
Rhebuck (grey)	**8**	**10**	**3**	**3**	**5**	
Rhino (black)	**5**		**10**	**10**	**15**	
Steenbok	**5**	**5**	**3**	**3**	**5**	**5**

***LSU: large stock unit.**

Appendix 4B Minimum herd size and relative distribution of animal species per ecological region for smaller farms (ABSA, 2003)

		Relative distribution of animal species as a % of LSU*				
Animal species	**Min. social herd size**	**Grassland**	**Lowveld**	**Bushveld**	**Kalahari**	**Karoo**
Low selective grazers		**20%**	**25%**	**20%**	**10%**	**2%**
Buffalo	15		50			
Zebra (Burchell)	5	100	50	100		
Zebra (Cape mountain)	10				100	100
High selective grazers		**50%**	**30%**	**30%**	**65%**	**60%**
Blesbok	12	20				
Gemsbok	12				30	30
Red hartebeest	12	10		10	10	10
Reedbuck	8	5	5	5		
Springbok	15	20			30	30
Tsessebe	12		15	15		
Waterbuck	12		20	20		
Wildebeest (black)	12	45				
Wildebeest (blue)	12		60	50	30	30
Mixed feeders		**28%**	**25%**	**30%**	**20%**	**35%**
Duiker	6	2	2	2	2	3
Eland	12	95			43	92
Impala	15		60	70	25	
Nyala	12		10			
Ostrich	6		10	10	10	5
Reedbuck (mountain)	8	3	3	3	5	
Warthog	12		15	15	15	
Browsers		**2%**	**20%**	**20%**	**5%**	**3%**
Bushbuck	8		5	5		
Giraffe	8		55	50		
Klipspringer	4	15	2	2	5	10
Kudu	12		30	35	85	
Rhebuck (grey)	8	45	5	5		
Steenbok	5	40	3	3	10	90

*LSU: large stock unit.

Appendix 4A.2 Breakdown of animal species, energy requirements, diet characteristics, intake and annual enteric methane emissions

Animal Species	Animal characteristics		LSU	Diet characteristics		Intake (kg DM/ day)	Intake (%/LW)	CH_4 kg/h/year
	Weight (kg)	ME requirements (MJ/day)		Diet DE%	ME MJ/kg			
Elephant								
Calf (5 years)	850	84.8	1.13	55	8.3	10.2	1.2	23.9
Cow, dry (15 years)	1850	285	3.80	55	8.3	34.3	1.9	80.4
Cow, dry (50 years)	3300	291	3.88	55	8.3	35.1	1.1	82.1
Cow with calf (15 years)	1850	362	4.83	55	8.3	43.6	2.4	102.1
Cow with calf (50 years)	3300	375	5.00	55	8.3	45.2	1.4	105.8
Bull (15 years)	2200	303	4.04	55	8.3	36.5	1.7	85.5
Bull (50 years)	3700	310	4.13	55	8.3	37.3	1.0	87.5
Average	2435.7	287.3	3.83	55	8.3	34.6	1.4	81.0
Giraffe								
Calf (9 months)	390	57.8	0.77	65	9.81	5.9	1.5	63.8
Cow, dry (5 years)	770	111.0	1.48	65	9.81	11.3	1.5	132.9
Cow, dry (10 years)	850	101.0	1.35	65	9.81	10.3	1.2	119.9
Cow with calf (5 years)	770	139.0	1.85	65	9.81	14.2	1.8	169.3
Cow with calf (10 years)	850	130.0	1.73	65	9.81	13.3	1.6	157.6
Bull (5 years)	960	126.0	1.68	65	9.81	12.8	1.3	152.4
Bull (6 years)	1190	127.0	1.69	65	9.81	12.9	1.1	153.7
Average	825.7	113.1	1.51	65	9.81	11.5	1.4	135.6
Eland								
Calf (8 months)	200	38.9	0.52	65	9.81	4.0	2.0	39.3
Cow dry (3 years)	460	75.5	1.01	65	9.81	7.7	1.7	86.8
Cow dry (6 years)	500	72.1	0.96	65	9.81	7.3	1.5	82.4
Cow with calf (3 years)	460	96.6	1.29	65	9.81	9.8	2.1	114.2
Cow with calf (6 years)	500	87.1	1.16	65	9.81	8.9	1.8	101.9
Bull (3 years)	760	99.5	1.33	65	9.81	10.1	1.3	118.0
Bull (6 years)	815	96.0	1.28	65	9.81	9.8	1.2	113.4
Average	528	80.8	1.1	65	9.81	8.2	1.6	93.7

LSU: large stock unit; ME: metabolizable energy; DE: digestibility; DM: dry matter; LW: live weight; CH_4: methane; kg/h/year = kg/head/year.

Appendix 4A.2 Breakdown of animal species, energy requirements, diet characteristics, intake and annual enteric methane emissions

Animal species	Animal characteristics		LSU	Diet characteristics		Intake (kg DM/ day)	Intake (%/ LW)	CH_4 (kg/h/year)
	Weight (kg)	ME requirements (MJ/day)		Diet DE%	ME (MJ/kg)			
Buffalo								
Calf (8 months)	145	31.8	0.42	55	8.3	3.8	2.6	37.6
Cow dry (4 years)	460	79.1	1.05	55	8.3	9.5	2.1	110.2
Cow dry (10 years)	530	76.4	1.02	55	8.3	9.2	1.7	106.0
Cow with calf (4 years)	460	101.0	1.35	55	8.3	12.2	2.6	143.2
Cow with calf (10 years)	530	99.3	1.32	55	8.3	12.0	2.3	141.2
Bull (4 years)	500	89.6	1.19	55	8.3	10.8	2.2	126.3
Bull (10 years)	640	87.7	1.17	55	8.3	10.6	1.7	123.4
Average	466.4	80.7	1.08	55	8.3	9.7	2.1	112.6
Zebra								
Foal (5 months)	95	24.6	0.33	55	8.3	3.0	3.1	6.9
Mare dry (4 years)	270	48.9	0.65	55	8.3	5.9	2.2	13.8
Mare dry (7 years)	290	45.0	0.60	55	8.3	5.4	1.9	12.7
Mare with foal (4 years)	270	61.0	0.81	55	8.3	7.3	2.7	17.2
Mare with foal (7 years)	290	58.9	0.79	55	8.3	7.1	2.4	16.6
Stallion (4 years)	310	54.0	0.72	55	8.3	6.5	2.1	15.2
Stallion (7 years)	335	52.1	0.69	55	8.3	6.3	1.9	14.7
Average	265.7	49.2	0.66	55	8.3	5.9	2.2	13.9
Kudu								
Calf (6 months)	55	15.8	0.21	65	9.81	1.6	2.9	9.3
Cow dry (3 years)	125	27.9	0.37	65	9.81	2.8	2.3	25.0
Cow dry (5 years)	160	29.8	0.40	65	9.81	3.0	1.9	27.5
Cow with calf (3 years)	125	34.9	0.47	65	9.81	3.6	2.8	34.1
Cow with calf (5 years)	160	38.7	0.52	65	9.81	3.9	2.5	39.0
Bull (3 years)	220	42.1	0.56	65	9.81	4.3	2.0	43.4
Bull (5 years)	240	39.9	0.53	65	9.81	4.1	1.7	40.6
Average	155	32.7	0.44	65	9.81	3.3	2.2	31.3

LSU: large stock unit; ME: metabolizable energy; DE: digestibility; DM: dry matter; LW: live weight; CH_4: methane; kg/h/year = kg/head/year.

Appendix 4C Breakdown of animal species, energy requirements, diet characteristics, intake and annual enteric methane emissions

Animal species	Animal characteristics		LSU	Diet characteristics		Intake (kg DM/ day)	Intake (%/LW)	CH_4 (kg/h/day)
	Weight (kg)	ME requirements (MJ/day)		Diet DE%	ME MJ/kg			
Waterbuck								
Lamb (5 months)	47	15.0	0.20	55	8.3	1.8	3.8	11.8
Ewe dry (3 years)	130	27.6	0.37	55	8.3	3.3	2.6	31.1
Ewe dry (5 years)	160	28.1	0.37	55	8.3	3.4	2.1	31.9
Ewe with lamb (3 years)	130	34.6	0.46	55	8.3	4.2	3.2	41.9
Ewe with lamb (5 years)	160	36.6	0.49	55	8.3	4.4	2.8	44.9
Ram (3 years)	195	37.3	0.50	55	8.3	4.5	2.3	46.0
Ram (5 years)	225	35.6	0.47	55	8.3	4.3	1.9	43.4
Average	149.6	30.7	0.41	55	8.3	3.7	2.5	35.9
Blue wildebeest								
Calf (4 months)	51	15.6	0.21	75	11.32	1.4	2.7	6.3
Cow dry (3 years)	145	29.8	0.40	75	11.32	2.6	1.8	22.3
Cow dry (5 years)	160	29.4	0.39	75	11.32	2.6	1.6	21.8
Cow with calf (3 years)	145	37.3	0.50	75	11.32	3.3	2.3	30.7
Cow with calf (5 years)	160	38.3	0.51	75	11.32	3.4	2.1	31.9
Bull (3 years)	195	37.2	0.50	75	11.32	3.3	1.7	30.6
Bull (5 years)	215	36.3	0.48	75	11.32	3.2	1.5	29.6
Average	153	32.0	0.43	75	11.32	2.8	1.8	24.8
Black wildebeest								
Calf (4 months)	40	12.5	0.17	75	11.32	1.1	2.8	8.2
Cow dry (3 years)	105	20.3	0.27	75	11.32	1.8	1.7	12.9
Cow dry (5 years)	115	21.6	0.29	75	11.32	1.9	1.7	13.7
Cow with calf (3 years)	105	25.4	0.34	75	11.32	2.2	2.1	15.7
Cow with calf (5 years)	115	28.2	0.38	75	11.32	2.5	2.2	17.7
Bull (3 years)	125	25.1	0.33	75	11.32	2.2	1.8	15.8
Bull (5 years)	135	25.3	0.34	75	11.32	2.2	1.7	15.9
Average	105.7	22.6	0.30	75	11.32	2.0	1.9	14.3

LSU: large stock unit; ME: metabolizable energy; DE: digestibility; DM: dry matter; LW: live weight; CH_4: methane; kg/h/year = kg/head/year.

Appendix 4D Breakdown of animal species, energy requirements, diet characteristics, intake and annual enteric methane emissions

Animal species	Animal characteristics		LSU	Diet characteristics		Intake (kg DM/ day)	Intake (%/LW)	CH_4 (kg/h/day)
	Weight (kg)	ME requirements (MJ/day)		Diet DE%	ME MJ/kg			
Tsessebe								
Lamb (5 months)	38	12.2	0.16	65	11.32	1.1	2.8	8.0
Ewe dry (3 years)	104	19.6	0.26	65	11.32	1.7	1.7	12.5
Ewe dry (5 years)	113	20.9	0.28	65	11.32	1.8	1.6	13.3
Ewe with lamb (3 years)	104	24.6	0.33	65	11.32	2.2	2.1	15.5
Ewe with lamb (5 years)	113	27.2	0.36	65	11.32	2.4	2.1	17.1
Ram (3 years)	126	24.2	0.32	65	11.32	2.1	1.7	15.3
Ram (5 years)	138	24.2	0.32	65	11.32	2.1	1.5	15.3
Average	105.1	21.8	0.29	65	11.32	1.9	1.8	13.8
Blesbok								
Lamb (5 months)	23	7.6	0.10	75	11.32	0.7	2.9	5.2
Ewe dry (3 years)	60	12.3	0.16	75	11.32	1.1	1.8	8.0
Ewe dry (5 years)	67	14.7	0.20	75	11.32	1.3	1.9	9.5
Ewe with lamb (3 years)	60	15.4	0.21	75	11.32	1.4	2.3	9.9
Ewe with lamb (5 years)	67	19.1	0.25	75	11.32	1.7	2.5	12.2
Ram (3 years)	73	14.3	0.19	75	11.32	1.3	1.7	9.3
Ram (5 years)	81	14.8	0.20	75	11.32	1.3	1.6	9.6
Average	61.6	14.0	0.19	75	11.32	1.2	2.0	9.1
Warthog								
Piglet (3 months)	13	6.2	0.08	75	11.32	0.5	4.2	3.6
Sow dry (2 years)	59	15.0	0.20	75	11.32	1.3	2.2	1.9
Sow dry (3 years)	65	13.9	0.19	75	11.32	1.2	1.9	1.6
Sow with litter (2 years)	59	21.1	0.28	75	11.32	1.9	3.2	2.7
Sow with litter (3 years)	65	20.1	0.27	75	11.32	1.8	2.7	2.3
Boar (2 years)	74	18.4	0.25	75	11.32	1.6	2.2	1.9
Boar (3 years)	80	16.2	0.22	75	11.32	1.4	1.8	1.5
Average	59.3	15.8	0.21	75	11.32	1.4	2.4	2.2

LSU: large stock unit; ME: metabolizable energy; DE: digestibility; DM: dry matter; LW: live weight; CH_4: methane; kg/h/year = kg/head/year.

Appendix 4E Breakdown of animal species, energy requirements, diet characteristics, intake and annual enteric methane emissions

Animal species	Animal characteristics		LSU	Diet characteristics		Intake (kg DM/ day)	Intake (%/LW)	CH_4 (kg/h/day)
	Weight (kg)	ME requirements (MJ/day)		Diet DE%	ME MJ/day			
Impala								
Lamb (4 months)	19	5.8	0.08	75	11.32	0.5	2.7	4.1
Ewe dry (2 years)	37	10.8	0.14	75	11.32	1.0	2.6	7.1
Ewe dry (4 years)	45	10.2	0.14	75	11.32	0.9	2.0	6.8
Ewe with lamb (2 years)	37	14.0	0.19	75	11.32	1.2	3.3	9.1
Ewe with lamb (4 years)	45	13.9	0.19	75	11.32	1.2	2.7	9.0
Ram (2 years)	51	11.9	0.16	75	11.32	1.1	2.1	7.8
Ram (4 years)	60	12.2	0.16	75	11.32	1.1	1.8	8.0
Average	42	11.3	0.15	75	11.32	1.0	2.4	7.4
Springbok								
Lamb (2.5 months)	12	3.2	0.04	75	11.32	0.3	2.3	2.5
Ewe dry (18 months)	27	6.3	0.08	75	11.32	0.6	2.1	4.4
Ewe dry (3 years)	31	7.0	0.09	75	11.32	0.6	2.0	4.8
Ewe with lamb (18 months)	27	7.9	0.10	75	11.32	0.7	2.6	5.3
Ewe with lamb (3 years)	31	9.1	0.12	75	11.32	0.8	2.6	6.1
Ram (18 months)	30	7.1	0.09	75	11.32	0.6	2.1	4.9
Ram (3 years)	36	7.4	0.10	75	11.32	0.7	1.8	5.0
Average	27.7	6.8	0.09	75	11.32	0.6	2.2	4.7

LSU: large stock unit; ME: metabolizable energy; DE: digestibility; DM: dry matter; LW: live weight; CH_4: methane; kg/h/year = kg/head/year.

Chapter 5

Direct methane and nitrous oxide emissions of monogastric livestock in South Africa

C.J.L. du Toit[1,2,#], W.A. van Niekerk[2] and H.H. Meissner[3]
[1] Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa
[2] Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[3] 189 van Riebeeck Avenue, Lyttelton Manor, Centurion, 0157, South Africa

Abstract
There are increasing concerns about the impact of agriculture and livestock production on the environment. In this the greenhouse gas emissions (GHG) from South African pigs, ostriches, horses, donkeys, mules and poultry were calculated, using 2010 production data on a provincial basis. The Intergovernmental Panel on Climate Change (IPCC, 2006) methodology adapted to tropical production systems was used to calculate methane (CH_4) and nitrous oxide (N_2O) emissions. The non-ruminant sector is a minor GHG contributor compared with ruminant CH_4 and N_2O emissions. The pig industry and ostrich industry both contribute approximately 8 Gg (Giga gram) CH_4 /year. The poultry industry is the largest direct N_2O producer of the non-ruminant livestock industries, contributing 2.3 Gg/year or 92.8% of the total non-ruminant N_2O emissions.

Keywords: Greenhouse gas, pigs, horses, ostriches, broiler, layer
[#]Corresponding author: dutoitcjl@tut.ac.za

Introduction

Livestock production systems contribute directly and indirectly to atmospheric anthropogenic greenhouse gases through the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The agricultural sector, including livestock, forest land and cropland (carbon sinks), wetlands and emissions from biomass burning in South Africa, contributes an estimated 4.7% to the total national GHG (greenhouse gas) emissions (DEAT, 2009). This places agriculture third after the energy sector (79%) and industrial processes (14%) in terms of greenhouse gas emissions (DEAT, 2009). Livestock was reported to contribute 98% of the agricultural sector's methane emissions (Otter, 2010), making livestock a key methane emitting source, producing approximately 27.4% of national methane emissions. Methane and nitrous oxide are both potent greenhouse gases with 21 to 25 times and 298 to 310 times the global warming potential of carbon dioxide for methane and nitrous oxide, respectively (FAO, 2006; IPCC, 2006; Eckard *et al.*, 2010).

An inventory methodology should follow international guidelines, as developed by the Intergovernmental Panel on Climate Change (IPCC, 2006) to ensure consistency and comparability between inventories and countries (Exnerova and Cienciala, 2009). The IPCC followed a hierarchical approach of Tier 1 through to Tier 3 methodologies. Tier 1 methods are the crudest methodology, characterized by simple calculations based on aggregated statistical data and the use of developed default emission factors. Tier 2 methods are based on more

detailed statistical data and emission factors derived from calculations using country-specific inputs. Finally, the Tier 3 method is the most sophisticated, requiring country-specific emission factors developed through direct measurements carried out under local or regional conditions (Exnerova and Cienciala, 2009).

Greenhouse gas emissions from livestock vary by animal type, growth stage and level of production owing to different diets (diet quality, digestibility and forage: concentrate ratio), feed conversion mechanisms and manure management systems (Chadwick *et al*., 2000; Borhan *et al*., 2012; Zervas and Tsiplakou, 2012). Emissions from animal manure and waste management systems are influenced by soil and manure moisture, temperature, manure loading rate by the animal, depth of manure in the pen, redox potential, available carbon, diets and microbial processes (Borhan *et al*., 2012). Ruminants are the main methane contributors in the livestock industry owing to their digestive process in which carbohydrates are degraded by micro-organisms and methane is released as a by-product of enteric fermentation (Stevens and Hume, 1995; Wang and Huang, 2005). Non-ruminants also contribute to methane emissions through enteric fermentation in the caecum and large intestine, but in much smaller quantities than ruminants (Wang and Huang, 2005). Nitrous oxide is produced during the biological transformation of mineral nitrogen (N) through nitrification, which converts ammonium (NH_4^+) nitrogen into nitrate (NO_3^-), and denitrification, which reduces nitrate to molecular nitrogen (N_2). According to Duval and Paquin (2009) denitrification produces approximately 10% more N_2O than nitrification per unit of transformed nitrogen.

Previous inventories documenting GHG emissions from South African livestock (Blignaut *et al*., 2005; DEAT, 2009; Otter, 2010) were conducted on a national scale, utilizing IPCC default values (Tier 1 approach) for some or all of their emission calculations. These emission factors do not distinguish effectively between classes of animals, production efficiencies and production systems. They are often based on assumptions of animals utilizing highly digestible diets and temperate forages (Mills *et al*., 2001), which are not representative of South African production systems.

It is essential to obtain accurate estimates of GHG emissions from all sources in livestock production systems (animals, intensive housing, pens and kraals, manure handling facilities, silage bunkers, grazing lands, etc.) to improve emissions inventories and to develop source and country-specific abatement strategies. The objective of this paper is to review the methane and nitrous oxide emissions related to non-ruminant livestock in South Africa in total as well as per province, using the Tier 2 approach.

Materials and Methods

The methodology was based on the Australian national greenhouse accounts, National Inventory Report (ANIR, 2009), which contains Australian country-specific and IPCC default methodologies and emission factors. A Tier 2 approach has been adopted for swine emission calculations in accordance with the IPCC Good Practice requirements (IPCC, 2006). The emissions from ostriches, horses, donkeys, mules and poultry were calculated on a Tier 1 approach owing to a lack of activity data and the relatively small contribution of these animal categories. The inventory was compiled on a provincial basis where possible to reduce errors associated with averaging input data across areas with large physical and managerial differences. The provincial totals are aggregated to give national totals. The inventory was based on 2010 population data.

Non-ruminants (e.g. pigs, horses, mules, ostriches and poultry) do produce enteric methane in the large intestine, but the amount of methane produced is significantly less on a per animal basis than ruminants (EPA, 2013). The amount of enteric methane produced is influenced by the animal's digestive system, feed quality and the feed intake. The population numbers for all non-ruminant livestock in South Africa are based on figures provided by the Abstract of Agricultural Statistics (StatsSA, 2010), Department of Agriculture, Forestry and Fishery statistics (DAFF, 2010) and industry associations (SAPPO, 2011; NOPSA, 2011; SAPA, 2011). These figures were cross-referenced with slaughter and production data (SAPPO, 2011; NOPSA, 2011; SAPA, 2011).

The population numbers for commercial and communal (emerging and subsistence) pigs were calculated from the number of sows per province according to the average composition of a 100-sow unit as presented in Table 5.1 (SAPPO, 2011). To accommodate the use of artificial insemination in commercial pig production systems the number of breeding boars was reduced from 6 to 3 per 100 sow unit (Table 5.1).

Pigs are typically fed concentrate-based diets, especially in the commercial sector, and convert approximately 1% of gross energy intake (GEI) into methane compared with 6% - 7% for cattle and sheep (OECD, 1991). Methane conversion values for pigs are reported to be between 0.4% and 1.2% (Kirchgessner *et al*., 1991; Moss, 1993). A methane conversion factor of 0.7% was used in the calculation for pigs based on the ANIR (2009). Daily intake and diet data for all classes of commercial and communal pigs were sourced from SAPPO (2011).

The total daily methane production (M), (kg CH_4/head/day) from enteric fermentation in pigs was calculated based on the ANIR (2009) as:

$M = I \times 18.6 \times 0.007 / F$ …… Equation 1

Where: I = Intake (kg DM/day) (Appendix 5A.1)
F = 55.22 MJ/kg CH_4 (Brouwer, 1965)
18.6 = MJ GE/kg feed DM

Table 5.1 Composition of a 100 sow pig unit in South Africa (SAPPO, 2011)

	Commercial production systems	Communal production systems
Boars	3	6
Dry gestating sows	90	90
Lactating sows	16	16
Replacement sows	25	25
Replacement boars	3	3
Pre-wean piglets	160	80
Cull sows	25	25
Cull boars	3	3

The enteric methane emission factors from all other non-ruminant or monogastric livestock, including ostriches (5 kg CH_4/head/year), horses (18 kg CH_4/head/year), donkeys and mules

(10 kg CH_4/head/year), were sourced from the IPCC (2006), and the total methane emissions were calculated using population data and an annual methane emission factor. These emission factors are based on the work of Crutzen *et al*. (1986), who reported values for developing and developed countries and values recorded in the ANIR (2009). Currently an enteric methane emission factor is not reported for poultry (broilers or layers) in the IPCC (2006) good practice guidelines.

Manure emissions

The management of livestock manure can produce anthropogenic methane and nitrous oxide emissions (EPA, 2013). Commercial pig production systems in South Africa are housed systems, and a large proportion of manure and waste is managed in lagoon systems. These lagoon systems create anaerobic conditions, resulting in a high proportion of the volatile solids being fermented, which leads to the production of methane (ANIR, 2009). The volatile solid production (VS), (kg/head/day) from pig manure was calculated according to the IPCC (2006) as:

$VS = [GE \times (1 - (DE\%/100)) + (UE \times GE)] \times [(1 - Ash)/18.45]$ …….…….. Equation 2

Where:
GE = Gross energy intake (MJ/day)
DE% = digestibility of feed (%) (Appendix 5A.1)
(UE x GE) = urinary energy expressed as a fraction of GE. (Typically, 0.02GE for pigs, IPCC, 2006)
Ash = Ash concentration of manure (17%), (F.K. Siebrits, 2012, Pers. Comm., Dept. Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001)
18.45 = conversion factor for dietary GE per kg of DM (MJ/kg)

Methane produced from manure (M), (kg/head/day) and wasted feed was calculated according to the ANIR (2009) as:

$M = VS \times B_o \times MCF \times p$…….. Equation 3

Where:
VS = volatile solid production (kg/head/day)
B_o = emissions potential (0.45 m^3 CH_4/kg VS) (IPCC 2006)
MCF = integrated methane conversion factor. Based on the different manure management systems (Appendix 5A.3)
p = density of methane (0.662 kg/m^3)

Volatile solid production from poultry production systems was calculated based on the ANIR (2009) utilizing intake data and diet dry matter digestibilities as:

$VS = I \times (1 - DMD) \times (1 - Ash)$ ..…… Equation 4

Where =
VS = volatile solid production (kg/head/day)
I = dry matter intake (assumed to be 0.11 kg/day), (ANIR, 2009)
DMD = dry matter digestibility (assumed to be 80%), (ANIR, 2009)
Ash = ash concentration (assumed to be 8% of faecal DM), (ANIR, 2009)

Methane production from poultry manure (M) (kg/head/day) was calculated according to Equation 3, using a MCF of 1.5% according to the IPCC (2006). Ostriches, horses, donkeys

and mules are kept on the veld in extensive systems with a relatively small amount of methane being produced from manure. Methane production from manure (M) (kg/head/day) originating from these sources was calculated as:

$M = DMM \times MEF$ ……. Equation 5

Where: DMM = dry matter in manure (Appendix 5A.5.2)
MEF = manure emission factor (kg CH_4/kg DM manure) taken as 1.4×10^{-5} kg CH_4/kg DMM (Gonzalez-Avalos and Ruiz-Suarez, 2001).

The nitrous oxide emissions from pig production systems were calculated according to ANIR (2009). The annual nitrogen (AE, kg/year) from pig manure and wasted feed was calculated as:

$AE = N \times E$ …….. Equation 6

Where: N = number of each category of pigs per province
E = nitrogen in waste (kg/head/year) (Appendix 5A.5.1 and 5A.6.1)

The total nitrous oxide emission (E), (kg) from pigs was calculated as:

$E = (AE \times MMS \times EF \times C_g)$ …… Equation 7

Where: MMS = the fraction of AE that is managed in the different manure management systems (Appendix 5A.3)
EF = emission factor (N_2O-N kg/ N excreted) to the different MMS (Appendix 5A.6.2)
C_g = 44/28 factor to convert the elemental mass of N_2O to molecular mass

The nitrogen excretion from poultry was calculated based on the ANIR (2009) using the average intake for broilers and layers (0.11 kg DM/head/day), with approximately 19% crude protein for broilers and 16.5% for layers. According to the NRC (1994), poultry are assumed to retain 43% of nitrogen intake, which gives a nitrogen excretion rate of 0.7 kg N/bird/year and 0.6 kg N/bird/year for broilers and layers, respectively. The total N_2O emissions from the various poultry production systems were then calculated using Equation 7 and assuming an emission factor of 0.02 kg N_2O-N/ kg N excreted for broilers and 0.005 kg N_2O-N/kg N excreted for layer chickens according to the ANIR (2009).

The direct nitrogen excretion rate for all other non-ruminant or monogastric livestock (ostriches, horses, donkeys and mules) was based on a ratio of the nitrogen excretion rates of sheep and cattle and animal size (ANIR, 2009). The nitrogen excretion rates are presented in Table 5A.5.3 in Appendix 5A. The nitrogen excreted by these livestock categories was calculated according to Equation 6 and the total N_2O emissions from the various manure management systems were calculated according to Equation 7. It was assumed that 40% of horse manure was managed in a drylot system and 60% was voided while the animals were at pasture. All manure from ostriches, donkeys and mules were assumed to be voided while the animals were at pasture. Emissions of N_2O from soils related to livestock production systems are not included in the present review. These emissions arise from microbial and chemical transformations that produce and consume N_2O in soil. Nitrogen compounds can be added to soil through the application of animal wastes and sewage sludge to pastures, leaching from soils and surface runoff of N and subsequent denitrification in water bodies, and N_2O through the metabolism of urine and faeces deposited directly on pastures or rangeland.

Results and Discussion

The amount of enteric methane produced by pigs is influenced largely by the fibre content of the diet and is significantly less than CH_4 produced by ruminants on a per animal basis (EPA, 2013). Manure is the largest direct GHG emissions source in commercial and communal (emerging and subsistence) pork production systems. Liquid manure storage is the most common manure management practice in South African commercial pig production systems, representing 93.5% of all manure management (SAPPO, 2011). The communal pig sector is based more on semi-intensive or extensive production systems, with manure being deposited on pasture (50%) or stored in drylot systems (50%) (SAPPO, 2011). The methane conversion factors (MCF) for liquid manure handling facilities are much higher than when manure is managed in a drylot system or spread on pastures with 90% and 35% MCF for lagoons and slurries compared with 1.5% and 0.5% for drylot and daily spread of manure (ANIR, 2009).

The direct methane and nitrous oxide emission factors (kg/head/year) for the pig industry were calculated using a Tier 2 approach and are presented in Table 5.2 and Table 5.3. The emission factors were calculated according to an average herd structure (SAPPO, 2011), live weight (A.T. Browne, 2012, Pers. Comm., Dept. Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001) and intake (SAPPO, 2011) for commercial and communal pig production systems.

Lactating sows were the highest emitters of CH_4 and N_2O, followed by replacement animals, dry gestating sows, boars and grower animals. Lactating sows had the highest nutrient requirements and intake, which explains the higher emission factors reported in Table 5.2 and 3.

Table 5.2 Direct methane and nitrous oxide emissions factors for South African commercial pigs

	Weight (kg)	Enteric CH_4 (kg/h/year)*	Manure CH_4 (kg/h/year)*	N_2O (kg/h/year)*
Boars	300	1.89	16.47	0.045
Dry gestating sows	350	2.15	18.71	0.064
Lactating sows	300	4.09	35.55	0.064
Replacement sows	135	2.41	20.96	0.038
Replacement boars	135	2.41	20.96	0.038
Pre-wean piglets	9	0.43	3.74	0.034
Cull sows	325	1.55	13.47	0.064
Cull boars	325	1.89	16.47	0.045
Porkers**	70	0.51	17.96	0.0084
Baconers***	90	0.99	20.96	0.014

* kg/head/year
** Porker slaughtered at 3 months age (90 days).
*** Baconer slaughtered at 5 months age (150 days).

The total and provincial emissions contributions of the pig industry are presented in Table 5.4. The South African pork industry produced an estimated 7.9 Giga gram (Gg) of CH_4 and 0.04 Gg of N_2O annually. The commercial pig sector is responsible for 7.64 Gg of the industry's methane emissions (97%) and 0.015 Gg of the industry's N_2O emissions (38.5%). Fifty per cent of the commercial pig sector's methane emissions originated from North West, KwaZulu-Natal and Western Cape, with 17.5%, 16.4% and 15.7%, respectively. The communal pig sector is dominated by Eastern Cape, contributing 50% of the sector's methane emissions with North West, KwaZulu-Natal and Western Cape each responsible for approximately 9% of the methane emissions, respectively. The communal pig sector is responsible for 3% of the industry methane emissions and produced approximately 0.024 Gg or 61.5% of the industry's total direct N_2O emissions. This is owing to the differences in manure management systems between the commercial and communal production systems (Appendix 5A.3) and the higher N emission factor of 0.02 compared with 0.001 (IPCC, 2006) for manure managed in drylot systems compared to lagoon or slurry systems.

In the previous livestock GHG inventory commissioned by the Department of Environmental Affairs and Tourism, which was based on 2004 data, the pork industry produced a total of 53.07 Gg of CH_4 and 0.891 Gg N_2O emissions. These figures are higher than the current estimated figures reported in Table 5.4, of 7.87 Gg for CH_4 and 0.04 Gg for N_2O, respectively. The previous inventory was conducted on a Tier 1 level, using IPCC default values for both methane and nitrous oxide emissions. There is a wide variation in population figures between the 2004 inventory and the current estimation. In the previous inventory, Otter (2010) based the population numbers on national statistics of approximately 2.6 million animals in 2004 (StatsSA, 2010).

Table 5.3 Direct methane and nitrous oxide emissions factors for South African communal pigs

	Weight (kg)	Enteric CH_4 (kg/h/year)*	Manure CH_4 (kg/h/year)*	N_2O (kg/h/year)*
Boars	240	1.55	0.37	0.23
Dry gestating sows	280	1.72	0.42	0.33
Lactating sows	240	3.27	0.79	0.33
Replacement sows	108	1.93	0.46	0.19
Replacement boars	108	1.93	0.46	0.19
Pre-wean piglets	7.2	0.34	0.08	0.17
Cull sows	260	1.24	0.30	0.33
Cull boars	260	1.55	0.37	0.23
Porkers**	70	0.41	0.40	0.042
Baconers***	90	0.79	0.46	0.07

* kg/head/year
** Porker slaughtered at 3 months age (90 days).
*** Baconer slaughtered at 5 months age (150 days).

The national statistics figures are not aligned with the population figures provided by the industry of approximately 600 000 animals in commercial and communal production systems across all provinces in 2010 (SAPPO, 2011). The aggregated CH_4 emissions (both enteric and manure) for all pigs were 20.73 kg/animal/year in 2004 compared with 13.19 kg/animal/year estimated on a Tier 2 level in the current estimation of 2010. The annual CH_4 emission per animal calculated in the current inventory (13.19 kg/animal/year) is higher than emissions reported by Verge *et al*. (2009) for the Canadian pork industry of 7.9 kg CH_4/animal/year and 11.6 kg CH_4/animal/year. The differences in the Canadian figures were mainly owing to differences in the diet digestibilities used in various regions (Verge *et al*., 2009).

The South African emission factors reported in Table 5.2 and Table 5.3 are compared with emission factors developed by other developing and developed countries in Table 5.5. The estimated enteric emission factors for commercial and communal pigs are higher than the IPCC (2006) default factors for developing countries, but are comparable with default values reported for developed countries such as North America, Canada and Australia. The estimated commercial manure methane emission factors are in line with IPCC (2006) values for developed countries and Australian country-specific values, but higher than emission factors reported by New Zealand, Canada and India. These differences are probably owing to variations in animal live weight, diet digestibility, intake and variations in manure management systems. The nitrogen excretion rate calculated for commercial and communal kept pigs in South Africa falls in the range of published data of 10.8 to 20.7 kg N/animal/year as reported in Table 5.5.

Greenhouse gas emissions reported from poultry production systems in South Africa are mainly methane and nitrous oxide emissions from manure. The IPCC (2006) does not include enteric methane emissions from poultry in emissions inventories, although Wang and Huang (2005) and Burns *et al*. (2008) did report on enteric methane emissions for broiler chickens of 3.77 x 10^{-7} kg/bird/day (42 day growth period) and 6.56 x 10^{-5} kg/bird/day (52-day growth period), respectively. The poultry emissions were calculated based on the IPCC (2006) Tier 1 approach using emissions factors reported in the ANIR (2009) for all classes of chickens (broilers, broiler parents, layers, and layer breeders). The methane and N_2O emission factors for South African broiler and layer production systems are presented in Table 5.6. A 34 day growth period was assumed for broiler production systems in South Africa with an average of 8 production cycles per year (A.F. Hill, 2013, Pers. Comm., Rainbow chicken contract grower, P.O. Box 2734, Westville, 3635).

Table 5.4 Provincial greenhouse gas emissions summary of South African pigs based on 2010 data (Gg/year)

Province	Commercial				Communal			
	Population	Enteric methane	Manure methane	N_2O	Population	Enteric methane	Manure methane	N_2O
Gauteng	51895	0.09	0.77	$1.6x10^{-3}$	7216	0.011	0.003	$1.4x10^{-3}$
Limpopo	53350	0.09	0.79	$1.7x10^{-3}$	7544	0.011	0.003	$1.5x10^{-3}$
Mpumalanga	64020	0.11	0.94	$2x10^{-3}$	8856	0.013	0.003	$1.7x10^{-3}$
North West	81480	0.14	1.20	$2.6x10^{-3}$	11152	0.016	0.004	$2.2x10^{-3}$
KZN	76145	0.13	1.12	$2.4x10^{-3}$	10496	0.016	0.004	$2x10^{-3}$
W Cape	73235	0.12	1.08	$2.3x10^{-3}$	10168	0.015	0.004	$2x10^{-3}$
Free State	41225	0.07	0.61	$1.3x10^{-3}$	5576	0.008	0.002	$1.1x10^{-3}$
Eastern Cape	21340	0.04	0.31	$6.7x10^{-4}$	61992	0.092	0.022	$1.2x10^{-2}$
N Cape	9215	0.02	0.02	$2.9x10^{-4}$	1640	0.002	0.0006	$3.2x10^{-4}$
Total	471905	0.8	6.84	0.015	124640	0.184	0.044	0.024

W Cape: Western Cape; N Cape: Northern Cape; KZN: KwaZulu-Natal.

Table 5.5 Comparison of calculated and published emission factors for pork from international sources

Source		Methane		Nitrogen excretion rate (kg/head/year)	Reference
		Enteric (kg/head/year)	Manure (kg/head/year)		
South Africa	Commercial	1.8	18.5	14.9	
	Communal	1.5	0.41	14.9	
IPCC: Africa	Developed	1.5	1.0		a
	Developing	1.0	1.0		
IPCC: Oceania	Breeding swine	1.5	23.0	20.0	
	Market swine	1.5	13.0	16.0	
IPCC: North America	Breeding swine	1.5	28.0		
	Market swine	1.5	15.0		
Australia		1.45	23.0	20.7	b
New Zealand		1.08	5.94	10.8	c
Brazil		1.0	1.0		d
Canada		1.5	10 - 10.4		e
India			4.37 - 4.50		f

a: IPCC (2006); b: ANIR (2009); c: NZNIR (2010); d: Lima *et al*. (2002); e: Kebreab *et al*. (2006); f: Chhabra *et al*. (2012).

Similar daily DM intake (0.11 kg/day) and diet DMD (80%) were assumed for both broiler and layer production systems, which resulted in a single manure methane emission factor (kg/head/day) for the poultry industry. Broilers have higher protein requirements when compared to layers (NRC, 1994), which explains the slightly higher N_2O emission factor for both broilers and broiler parents compared to layers.

The population data for all classes of poultry in South Africa were sourced from SAPA (2011) which combined the figures of Western Cape and Northern Cape provinces and Mpumalanga and Limpopo. For the purpose of this inventory the combined population figures were equally divided between the two provinces in question. The provincial contributions to poultry GHG emissions are presented in Tables 7 and 8. Poultry emissions estimated are only based on population figures for the commercial poultry industry as no data on poultry in communal production systems exist for South Africa.

Table 5.6 Methane and nitrous oxide emission factors of South African poultry (ANIR, 2009)

	Enteric CH_4 (kg/head/year)*	Manure CH_4 (kg/head/year)	N_2O (kg/head/year)#
Layers	0	0.0235	0.003
Layer breeders	0	0.0235	0.003
Broilers	0	0.0235	0.014
Broiler breeders	0	0.0235	0.014

* Enteric methane emissions reported for broilers from different sources of 3.77 x 10^{-7} kg/bird/day (Wang and Huang, 2005) and 6.56 x 10^{-5} kg/bird/day (Burns *et al*., 2008) were not incorporated.
# Representing direct N_2O emissions.

Table 5.7 Provincial direct greenhouse gas emissions (Gg/year) summary of South African broilers (2010)

Province	Broiler				Broiler breeders			
	Population ('000)	Enteric methane	Manure methane	N_2O	Population ('000)	Enteric methane	Manure methane	N_2O
W Cape*	10897	0	0.256	0.24	709	0	0.017	0.016
Eastern Cape	6850	0	0.161	0.15	448	0	0.011	0.010
N Cape*	10897	0	0.256	0.24	709	0	0.017	0.016
KZN	16309	0	0.383	0.36	1061	0	0.025	0.023
Free State	5658	0	0.133	0.12	365	0	0.009	0.008
North West	25713	0	0.604	0.57	1674	0	0.04	0.037
Gauteng	5658	0	0.133	0.12	365	0	0.009	0.008
Mpumal-anga*	11940	0	0.281	0.26	778	0	0.018	0.017
Limpopo*	11940	0	0.281	0.26	778	0	0.018	0.017
Total	105860	0	2.49	2.33	6888000	0	0.162	0.152

* Population numbers are combined in literature and were divided equally.
W Cape: Western Cape; N Cape: Northern Cape; KZN: KwaZulu-Natal.

The broiler industry is responsible for 81% of the poultry industry's methane emissions and 95% of the industry's N_2O emissions of 3.28 Gg and 2.6 Gg for CH_4 and N_2O, respectively. North West and KwaZulu-Natal were the biggest sole broiler producing provinces with 24.3% and 15.4% respectively of the national broiler population. The largest population of layers were found in Gauteng and the Free State, with 21% and 14.8% respectively. If enteric emission factors reported by Burns *et al*. (2008) are incorporated into the emissions estimation for both

broilers and layers, the total methane emissions from poultry production systems are increased by 68% to 5.8 Gg/year compared with 3.28 Gg/year, respectively.

The manure emission factors adopted for the present inventory are compared with international sources in Table 5.9. The emission factors utilized in the current emissions estimation fall within the range of international figures reported in Table 5.9.

The other non-ruminant or monogastric livestock classes of horses, donkeys, mules and ostriches are minor contributors to the livestock industry's GHG emissions and a Tier 1 approach was followed, using emission factors reported by ANIR (2009). The emission factors (kg/head/year) are presented in Table 5.10.

The horse industry contributes 4.86 Gg CH_4 per year. The largest provincial horse population is found in the Free State (DAFF, 2007; FAO, 2010) with 19% of South Africa's horse population. Limpopo has the lowest number of horses, contributing only 1.2% to the total. The provincial methane and nitrous oxide emissions from horses are reported in Table 5.11.

Table 5.8 Provincial direct greenhouse gas emissions (Gg/year) summary of South African layers (2010)

Province	Commercial				Layer breeders			
	Population ('000)	Enteric CH_4	Manure CH_4	N_2O	Population ('000)	Enteric CH_4	Manure CH_4	N_2O
W Cape*	2596	0	0.06	0.012	29	0	7×10^{-4}	0.000139
Eastern Cape	910	0	0.02	0.004	10	0	2×10^{-4}	4.81×10^{-5}
N Cape*	2596	0	0.06	0.012	29	0	$7x\ 10^{-4}$	0.000139
KZN	3670	0	0.09	0.017	42	0	1×10^{-3}	0.000197
Free State	4672	0	0.11	0.022	53	0	1.2×10^{-3}	0.00025
North West	2584	0	0.06	0.012	29	0	7×10^{-4}	0.000139
Gauteng	6596	0	0.16	0.031	75	0	1.8×10^{-3}	0.000352
Mpumalanga*	1415	0	0.03	0.007	16	0	4×10^{-4}	7.57×10^{-5}
Limpopo*	1415	0	0.03	0.007	16	0	4×10^{-4}	7.57×10^{-5}
Total	26454	0	0.62	0.125	300	0	7.1×10^{-3}	0.001414

* Population numbers are combined in literature and were divided equally.
W Cape: Western Cape; N Cape: Northern Cape; KZN: KwaZulu-Natal.

Table 5.9 Methane and nitrous oxide emission factors from poultry manure (kg/bird/year)

Source	Methane (kg/bird/year)	Nitrogen excreted (kg N/bird/year)	Reference
South Africa - 2010	0.0235	0.6 - 0.7	
South Africa: 2004	0.02 – 0.03	0.60 – 0.72	Otter, 2010
IPCC: Africa	0.02 – 0.03	0.6 – 1.10	IPCC (2006)
IPCC: Oceania	0.02 – 1.4	0.6 – 1.10	IPCC (2006)
Australia	0.02	0.6 – 0.7	ANIR (2009)
New Zealand	0.016 – 0.022	0.39 – 0.42	NZNIR (2010)
North America	0.1		EPA (2013)
Brazil	0.018 – 0.117		Lima *et al*. (2002)

Table 5.10 Methane and nitrous oxide emission factors for other non-ruminant livestock in 2010

Species	Enteric CH_4 (kg/head/year)	Manure CH_4 (kg/head/year)	N excreted (kg N/head/year)
Horses	18	0.0134	39.5
Donkeys	10	0.0045	13.2
Mules	10	0.0045	13.2
Ostriches	5	0.0016	7.0

Table 5.11 Provincial direct greenhouse gas emissions summary of horses (2010)

Province	Population	Enteric CH_4 (Gg/year)	Manure CH_4 (Gg/year)	N_2O (Gg/year)
Western Cape	37125	0.67	0.0005	0.012
Eastern Cape	43470	0.78	0.0006	0.014
Northern Cape	43921	0.79	0.0006	0.014
KwaZulu-Natal	45009	0.81	0.0006	0.014
Free State	51435	0.93	0.0007	0.016
North West	22923	0.41	0.0003	0.007
Gauteng	4590	0.08	6.15×10^{-5}	0.0015
Mpumalanga	18333	0.33	0.00025	0.006
Limpopo	3159	0.06	4.23×10^{-5}	0.001
Total	269965	4.86	0.004	0.086

The population figures for donkeys and mules were sourced from the FAO (2010). These species did not contribute direct N_2O emissions to the national total as they are kept exclusively in extensive production systems where all manure is voided at pasture. The methane emissions for donkeys and mules are reported in Table 5.12.

Table 5.12 Methane emissions of donkeys and mules (2010)

Species	Population	Enteric CH_4 (Gg/year)	Manure CH_4 (Gg/year)	Total CH_4 (Gg/year)
Donkeys	150500	1.51	0.00067	1.51
Mules	14200	0.142	6.34×10^{-5}	0.142

South Africa is the major supplier of ostrich products globally, and produces approximately 70% of all ostrich meat, leather and feathers to the world market (Brand and Jordaan, 2011). Ostriches are commercially farmed mainly in Western Cape and Eastern Cape with 60% of the ostrich population located in the Western Cape and 34% in the Eastern Cape (NOPSA, 2011). The provincial GHG emission summary of the ostrich industry is presented in Table 5.13. Ostrich manure is deposited directly on to veld and there are no direct nitrous oxide emissions attributed to ostrich production systems according to the IPCC (2006) guidelines.

Table 5.13 Provincial methane emissions summary of the South African ostrich industry

Province	Population	Enteric CH_4 (Gg/year)	Manure CH_4 (Gg/year)
Western Cape	960 000	4.8	0.00153
Eastern Cape	544 000	2.72	0.00087
Other	96 000	0.48	0.00015
Total	1600000	8.0	0.0026

Previous inventories for the South African livestock sector did not include ostriches or other poultry as emission sources. Ducks, geese and turkeys are minor livestock categories that do not contribute significantly to GHG emissions and are not commonly included in emissions inventories (Lima *et al*., 2002; ANIR, 2009; NZNIR, 2010). The emission calculations for the other poultry categories were done on a Tier 1 basis using IPCC (2006) default values of 0.03 kg /bird/year for duck and geese manure CH_4 emissions and 0.09 kg/bird/year for turkey manure CH_4 emissions. An annual nitrogen excretion rate of 0.6 kg/bird/year was assumed according to the IPCC (2006) with an emissions factor of 0.001 kg N_2O-N/ kg N excreted to calculate the N_2O emissions for the above poultry classes. Population data were sourced from the FAO (2010) as 375 000 ducks, 135 000 geese and 515 000 turkeys on a national scale. The estimated manure methane and nitrous oxide emissions (Gg/year) for ducks, geese and turkey were 0.011, 0.0041, 0.05 and 0.00023, 0.00008, and 0.00031, respectively.

Conclusion

Globally, swine, horses, ostriches and poultry are considered minor sources of GHG emissions contributing to total livestock emissions. A limited amount of research has been conducted to quantify direct emissions from these sources. The majority of published GHG emissions from pigs, equines and poultry are based on IPCC default values (Tier 1).The greenhouse gas contribution from non-ruminant (or monogastric) livestock in South Africa is minor compared with ruminant methane and N_2O emissions. Non-ruminant livestock are responsible for a total of 25.7 Gg methane emissions, with ostriches being the largest contributor, followed by pigs, horses, poultry and donkeys/mules with 31.1%, 30.6%, 18.9%, 12.8% and 6.4%, respectively. The poultry industry is the largest direct N_2O producer of the non-ruminant livestock industries with 2.25 Gg or 92.8% of the total N_2O emission originating from pigs, horses and poultry.

Acknowledgement

This work is based on the research supported wholly by the National Research Foundation of South Africa and the RMRD SA.

References

Australian National Inventory Report (ANIR), 2009. Australian national greenhouse accounts: National Inventory Report. Department of climate change and energy efficiency, Commonwealth of Australia, Canberra, ACT.

Blignaut, J.N., Chitiga-Mabugu, M.R. and Mabugu, R.M., 2005. Constructing a greenhouse gas inventory using energy balances: the case of South Africa 1998. J. Energy S. Afr. 16, 21-32.

Borhan, S., Mukhtar, S., Capareda, S. and Rahman, S., 2012. Greenhouse gas emissions from housing and manure management systems at confined livestock operations. In: Chapter 12, Waste management – An integrated vision. http://dx.doi.org/10.5772/51175.

Brand, T.S. and Jordaan, J.W., 2011. The contribution of the South African ostrich industry to the national economy. S. Afr. J. Anim. Sci. 4, 7-16.

Brouwer, E., 1965. Report of sub-committee on constants and factors. In: Proceedings of the 3rd Symposium on Energy Metabolism, Ed: Blaxter, K.L., London: Academic Press. pp. 441-443.

Burns, R.T., Li, H., Xin, H., Gates, R.S. and Overhults, D.G., 2008. Greenhouse (GHG) emissions from broiler houses in the Southern United States. Presented at the ASABE Annual International meeting, Rhode Island, June 29–July 2, 2008. Paper no 084649.

Chadwick, D.R., Pain, B.F. and Brookman, S.K.E., 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. J. Envir. Quality 29, 277-287.

Chhabra, A., Manjunath, K.R., Panigraphy, S. and Parihar., 2012. Greenhouse gas emissions from Indian livestock. Climate change, 117, 329 – 344.

Crutzen, P.J., Aselmann, I. and Seiler, W., 1986. Methane production by domestic animals, wild ruminants other herbivorous fauna and humans. Tellus 38B, 271-284.

DAFF, 2007. Department of Agriculture, Forestry and Fisheries - A profile of the South African market value chain, 2007. Directorate Marketing, Arcadia, Pretoria, South Africa.

DAFF, 2010. Department of Agriculture, Forestry and Fisheries - Livestock population statistics 2010. Pretoria, South Africa.

DEAT, 2009. Department of environmental affairs and tourism - Greenhouse gas inventory, South Africa. Communication under the United Nation Framework Convention on Climate Change. Pretoria, South Africa.

Duval, C. and Paquin, S., 2009. Swine production and greenhouse gases. Federation des producteurs de porcs du Quebec. Quebec, Canada.

Eckard, R.J., Grainger, C. and De Klein, C.A.M., 2010. Options for the abatement of methane and nitrous oxide from ruminant production: A review. Livest. Sci. 130, 47-56.

EPA, 2013. Environmental Protection Agency - Inventory of U.S. greenhouse gas emissions and sinks: 1990 - 2011. Washington D.C. EPA. http://epa.gov/climatechange/emissions/downloads/ GHG2013entire_report-508.pdf.

Exnerova, Z. and Cienciala, E., 2009. Greenhouse gas inventory of agriculture in the Czech Republic. Plant soil environ. 55, 311-319.

FAO, 2006. Food and Agriculture Organization of the United Nations, 2010. [Accessed on 5 March 2012]. FAOSTAT.

FAO, 2010. Food and Agriculture Organization of the United Nations, 2010. [Accessed on 5 March 2012]. FAOSTAT.

Gonzalez-Avalos, E. and Ruiz-Suarez, L.G., 2001. Methane emission factors from cattle manure in Mexico. Biosecure Technol. 80, 63-71.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

Kebreab, E., Clark, K., Wagner-Riddle, C. and France, J., 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci. 86, 135-158.

Kirchgessner, M., Kreuzer, M., Muller, H.L. and Windish, W., 1991. Release of methane and carbon dioxide by the pig. Agribiol. Res. 44, 103-113.

Lima, M.A., Young Pessoa, M.C.P. and Vieira Ligo, M.A., 2002. Methane emissions from livestock In: First Brazilian inventory of anthropogenic greenhouse gas emissions. Ministry of Science and Technology, Brazil.

Mills, J.A., Dijkstra, J., Bannik, A., Cammell, S.B., Krebreab, E. and France, J., 2001. A mechanistic model of whole tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation and application. J. Anim. Sci. 79, 1584-1597.

Moss, A.R., 1993. Methane: global warming and production by animals. Chalcombe publications. Kent, U.K.

New Zealand's greenhouse gas inventory, 2010. National Inventory Report (NZNIR) 1990 – 2010. http://www.mfe.govt.nz/publications/climate/nz-fifth-national-communication/html.

NOPSA, 2011. National Ostrich Processors of South Africa. Report to authors on ostrich numbers and production data, South Africa.

NRC, 1994. Nutrient Requirements of Poultry: Ninth revised edition, 1994. National Academy Press, Washington D.C., USA.

OECD, 1991. Estimation of GHG emissions and sinks. Final report from the OECD experts meeting 18 – 21 Feb 1991. The organisation for economic co-operation and development, Paris, France, Revised 1991.

Otter, L., 2010. The South African agricultural GHG inventory for 2004. Department of Agriculture, Forestry and Fisheries, South Africa, South Africa.

SAPA (South African Poultry Association), 2011. Report to authors on poultry numbers. SAPA, Johannesburg, South Africa.

SAPPO (South African Pork Producers Organisation), 2011. Report to authors on pig numbers in South Africa and production data. Pretoria, South Africa.

STATS South Africa, 2010. Statistics South Africa: Abstract of Agricultural Statistics. Directorate: Agriculture Statistics, DAFF, Pretoria, South Africa.

Stevens, C.E. and Hume, I.D., 1995. Comparative physiology of the vertebrate digestive system. Cambridge University Press, Cambridge, UK.

Verge, X.P.C., Dyer, J.A., Desjardins, R.L. and Worth, D., 2009. Greenhouse gas emissions from the Canadian pork industry. Livest. Sci. 121, 82-101.

Wang, S. and Huang, D., 2005. Assessment of greenhouse gas emissions from poultry enteric fermentation. Asian-Aust. J. Anim. Sci. 18, 873-878.

Zervas, G. and Tsiplakou, E., 2012. An assessment of GHG emissions from small ruminants in comparison with GHG emissions from large ruminants and monogastric livestock. Atmospheric Environ.49, 13-23.

Appendix 5A

Table 5A.1 Swine intake, diet composition and digestibility data (SAPPO, 2011)

Pig activity data	Intake (kg/day)		Gross energy intake (MJ/day)	Crude protein concentration %	Dry matter digestibility %	Digestible energy concentration (MJ/kg)
	Commercial	Communal				
Boars	2.2	1.8	33.21	13	92	13
Dry gestating sows	2.5	2.0	36.9	14	92	13
Lactating sows	4.75	3.8	70.11	13	92	13.5
Replacement sows	2.8	2.24	41.33	16	92	13.2
Replacement boars	2.8	2.24	41.33	16	92	13.2
Pre-wean piglets	0.5	0.4	7.38	18	92	14.5
Cull sows	1.8	1.44	26.57	14	92	13
Cull boars	2.2	1.8	33.21	13	92	13
Porkers	2.4	1.92	35.42	18	92	14
Baconers	2.8	2.24	41.33	18	92	14

Table 5A.2 Enteric methane emissions (kg/head/year) (ANIR, 2009)

Source	MEF (kg/head/year)
Horses	18
Donkeys and mules	10
Ostriches	5
Chickens and other poultry	Not estimated by IPCC (1997)

MEF: methane emission factor

Table 5A.3 Allocation of manure to manure management system (MMS) (%)

	Lagoon	Liquid/ slurry	Drylot	Daily spread	Digester
Commercial pigs	92	1.5	5	1.5	0
Communal pigs	0	0	50	50	0
Horses	0	0	40	60	0

Table 5A.4 Methane conversion factors (MCF), (%) of different manure management systems (ANIR, 2009)

	Lagoon	Liquid/ slurry	Drylot	Daily spread	Digester
MCF	90	35	1.5	0.5	10

Table 5A.5.1 Other monogastric livestock – enteric fermentation emission factors (kg CH_4/head/year) (ANIR, 2009)

	Horses	Donkeys and Mules	Ostriches	Poultry
All provinces	18	10	5	N.A

Table 5A.5.2 Other monogastric livestock - manure production (kg DM/head/year) (ANIR, 2009)

	Horses	Donkeys and Mules	Ostriches
All provinces	957	319	114

Table 5A.5.3 Other monogastric livestock – nitrogen excretion factors (kg N/head/year) (ANIR, 2009)

	Horses	Donkeys and Mules	Ostriches	Poultry – Broilers	Poultry - Layers
All provinces	39.5	13.2	7	0.7	0.6

Table 5A.6.1 Pigs – nitrogen (kg/head/year) entering the manure management system (MMS) (ANIR, 2009)

Breeding herd	Pig - kg N in MMS
Boars	14.59
Dry gestating sows	20.7
Lactating sows	20.7
Replacement sows	12.23
Replacement boars	12.23
Pre-wean piglets	11.04
Cull sows	20.7
Cull boars	14.59
Porkers (70 kg)	11.04
Baconers (90 kg)	11.04

Table 5A.6.2 Pigs - allocation of manure to manure management systems and nitrogen emissions factor (N_2O-N/ kg N excreted)

	Nitrogen emissions factor
Lagoon	0.001
Liquid/ slurry	0.001
Drylot	0.02
Daily spread	0
Digester	0.001

Chapter 6

Nutrient composition and *in vitro* methane production of sub-tropical grass species in transitional rangeland of South Africa

C.J.L du Toit[1,2#], W.A. van Niekerk[2], H.H. Meissner[3], L.J. Erasmus[2] and L Morey[4]

[1]Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa
[2]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[3]No 3 Die Hoewes, 276 von Willich Street, Centurion, 0157, South Africa
[4]ARC-Biomerty, ARC-Central Office, 1134 Park Street, Hatfield, 0087, South Africa
[#]Corresponding author: dutoitcjl@tut.ac.za; Tel: +27123824292; Fax: +27123825220

Abstract

The development of greenhouse gas mitigation strategies has become an important issue globally. Enteric methane emissions from livestock do not only contribute substantially to the environmental footprint of livestock production but it also represents a loss of energy that could be channelled towards animal growth and production. In this study fourteen sub-tropical grass species typical of transitional rangeland regions of South Africa were characterised in terms of ecological status, chemical composition, *in vitro* total and methane gas production. The aim of the study was twofold: to identify grass species that could be selected for low enteric methane production; and evaluate the influence of rangeland ecological status on the methanogenic potential of a rangeland. Grass samples were collected by hand, air dried, milled and analysed for nutrient composition, *in vitro* organic matter digestibility (IVOMD) and *in vitro* gas and methane (CH_4) production. *Cenchrus ciliaris* and *Urelytrum agropyriodes* produced the highest 48 hour *in vitro* CH_4 of 17.49 and 14.05 ml/ g DM digested respectively. The lowest 48 hour *in vitro* CH_4 was produced by *Andropogan gayanus* and *Bothriochloa bladhii* with 5.98 and 6.08 ml/ g DM digested respectively. The grass species evaluated was overall of poor quality with low crude protein (CP) concentrations ranging from 2.4% for *Trachypogon spicatus* to 6.7% for *Digitaria eriantha* and IVOMD ranging from 22.5% for *Andropogon gayanus* to 42.2% for *Urelytrum agropyriodes*. Decreaser grass species presented with higher *in vitro* methane production compared to Increaser I and Increaser II grass species in the present study. The results of the study emphasize the importance of including the nutritional potential of grass species for improved livestock production when evaluating grass species for possible greenhouse gas mitigation strategies.

Key words: nutritive value, fermentation, forage, quality, maturity, ecological status

Introduction

The livestock sector represents a significant source of greenhouse gas (GHG) emissions worldwide as well as in South Africa. Direct methane emissions by livestock, including privately owned game, was estimated at 1330 Gg CH_4/year and accounts for 95% of total livestock and 60% of total agricultural CO_2 equivalent emissions in South Africa (Meissner *et al*., 2013). Beef cattle, sheep and privately owned game rely mainly on extensive forage-based production systems accounting for 85% of total livestock methane emissions in South Africa (Du Toit *et al*., 2013a, b, c).

Southern African rangelands are extremely diverse in terms of botanical composition (Acocks, 1975), dry matter (DM) yield and nutritive value (De Waal, 1990). Variation in botanical composition and forage quality could allow for differences in methanogenic potential between rangelands in different ecological states and between different grass species (Meale *et al*., 2012; Gemeda and Hassen, 2014). The productivity of ruminant livestock in tropical and sub-tropical regions are limited by poor nutritional conditions characterised by highly lignified, low digestible feed from poor and often nitrogen (N) limited native rangeland and crop residues (Goel and Makkar, 2012). Ruminants fed on low quality forages represent a significant loss of dietary energy to CH_4 production that could potentially be redirected towards production of milk, meat and fibre (Eckard *et al*., 2010). Improving the quality of diets offered to livestock through selection of forage species, rangeland reinforcement and manipulating the ecological status of rangelands through improved management systems has the potential to reduce CH_4 emissions per unit animal product as a result of increased nutrient concentration, digestibility and reduced ruminal retention time of feed particles (Beauchemin *et al.,* 2009; Bannik *et al.,* 2013). Several researchers have investigated and screened different forage sources for methanogenic potential (Bodas *et al.,* 2008; Meale *et al.,* 2012; Dumeric *et al.,* 2016) focussing mainly on leguminous, non-leguminous shrubs, root forages, and temperate grass species with limited information on effects of specific sub-tropical grass species on enteric methane production. *In vitro* fermentation has been proven to be a successful method for the screening of forage fermentation characteristics and methanogenic potential (Durmic *et al.,* 2010; Doreau *et al.,* 2016). The objective of this study was to characterise sub-tropical grass species growing in transitional rangeland regions in South Africa based on ecological status, nutritional composition and methanogenic activity using *in vitro* fermentation to assist in the identification of sub-tropical grass species with potential for mitigation of enteric methane emissions from ruminants.

Materials and methods

Research site

The research was conducted on a 12 ha area of ecological stable natural rangeland typical to transitional rangeland or mixed rangeland areas in the northern Gauteng province of South Africa at the Hatfield Experimental Farm of the University of Pretoria. The site (28.11°E, 25.44°S, 1342 m alt) falls within a warm temperate climate, classified under the Cwa category of the Köppen-Geiger climate classification (Kottet *et al.,* 2006) and has average minimum and maximum temperatures of 11°C and 22.4°C respectively. The average annual rainfall is 674 mm with warm summer and dry autumn and winter seasons. The soil at the experimental site was classed as a sandy loam, with a pH (H_2O) of 6.1, and the following nutrient concentrations: Phosphorus (P) 33.9 mg/ kg, Calcium (Ca) 642 mg/ kg, Potassium (K) 115 mg/ kg, Magnesium (Mg) 188 mg/ kg, Sodium (Na) 12 mg/ kg, Ammonium (NH_4) 7.73 mg/ kg and Nitrate (NO_3) of 16.13 mg/ kg.

A comprehensive rangeland survey was conducted at the trial site to determine the species composition as described by Hardy *et al.* (1999). The trial site was divided into 4 equal blocks of 3 ha each. Samples of 14 grass species (*Poaceae* family) were collected at the end of the rainy season in April 2013, as described by Bezabih *et al.* (2013) when all species were in full bloom to ensure that all species were at a similar stage of physiological development. The grass species harvested were *Andropogon gayanus*, *Bothriochloa bladhii*, *Cenchrus ciliaris*, *Cymbopogon excuvatus*, *Digitaria eriantha*, *Elionurus miticus*, *Eragrostis curvula*, *Heteropogon contortus*, *Hyperthelia dissoluta*, *Panicum maximum*, *Panicum maximum* var Gatton, *Setaria megaphylla*, *Themeda triandra*, *Trachypogon spicatus* and *Urelytrum*

agroproides. Briefly, three transects were taken across each of the four blocks and grass samples were collected from 20 randomly positioned 1 m^2 quadrants along these transects. Grass species were identified and species occurring in each of the sample sites were cut by hand at 5 cm above the ground surface. Identified and selected grass species were harvested from each block in triplicate. The fourteen species were grouped into three ecological groups (Decreaser, Increaser I and Increaser II) according to Vorster (1982). Decreaser species is classified as species that decrease in number (% composition in the rangeland) during any form of over- or under- utilization; Increaser I species: species that increase in number during under-utilization; and Increaser II species: species that increase in number during over-utilization. Decreaser species identified and sampled were *Cenchrus ciliaris*, *Digitaria eriantha, Panicum maximum*, *Panicum maximum* var Gatton, *Setaria megaphylla*, and *Themeda triandra.* Increaser I species were *Andropogon gayanus*, *Bothriochloa bladhii*, *Cymbopogon excuvatus*, *Hyperthelia dissoluta*, *Trachypogon spicatus* and *Urelytrum agroproides*. Increaser II species were *Elionurus miticus*, *Eragrostis curvula*, and *Heteropogon contortus*. Samples were dried at 50°C for 48 hours and milled to pass through a 1mm sieve using a Retsch SM 100 mill (Retsch GmbH, Retsch-Allee 1-5, 42781, Haan, Germany). Milled samples were stored for chemical analysis.

Chemical analysis

Samples were analysed for parameters reported by Mills *et al.* (2003) to have an effect on forage quality and methane production. Samples were analysed in duplicate for dry matter (DM), ash concentration (Ash), ether extract (EE), and gross energy (GE) according to AOAC (2000). Neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) were analysed sequentially by using an Ankom Fiber Analyser (Ankom Technology) based on the method of Goering and Van Soest (1970) and total nitrogen (N) was analysed by combustion analysis (Leco FP-428, Leco Corporation). Hemicellulose was calculated as the difference between NDF and ADF (Hackmann *et al.*, 2008). Cellulose (Cell) was determined as ADF – ADL according to Moe and Tyrrell (1979).

In vitro digestibility, total gas and methane production measurement

Fermentation was determined by the procedure of Menke and Steingass (1988) as described by Getachew *et al.* (2005). Three rumen cannulated Döhne Merino wethers were used as rumen inoculum donors. The care, handling and maintenance of cannulated sheep were in accordance with animal welfare regulations of the animal ethics committee of the University of Pretoria (ECO18-14). The donor sheep were kept on a diet consisting of 50% rangeland hay, representative of the natural rangeland at the experimental site, and 50% *Medicago sativa* hay. Rumen fluid was collected from donor sheep two hours after the morning feeding, pooled, and filtered through two layers of cheese cloth. The rumen fluid was stored in a pre-warmed insulated thermos flask pre-filled with CO_2. Metabolizable energy (ME) was calculated from GE and *in vitro* organic matter digestibility according to Robinson *et al.* (2004) as ME (MJ/kg DM) = 0.81[(GE x IVOMD) / 100].

A semi-automated system was used to measure cumulative gas production through *in vitro* incubation at 39°C, according to Theodorou *et al.* (1994). The system consisted of a digital data logger (tracker 220 series indicators, Omega Engineering, Inc., Laval, QC, Canada) connected to a pressure transducer (PX4200-015GI from Omega Engineering, Inc., Laval, QC, Canada). The samples for gas analysis were incubated according to the procedure described by Theodorou *et al*. (1994). Approximately 400 mg of sample was weighed into 120 ml serum bottles. Filtered rumen fluid (15 ml) was mixed (1:2, v/v) with an anaerobic buffer/ mineral

solution prepared according to Goering and Van Soest (1970) with modifications suggested by Mould *et al*. (2005). After saturation with CO_2 the serum bottles were sealed with rubber stoppers and sealed with aluminum crimp seal caps. Possible gas build up was equalized by inserting a hypodermic needle through the rubber stopper for approximately 5 seconds. Thereafter the sample bottles were placed in an incubator at 39°C with a rotary shaker set at 120 rpm. The incubation and gas production measurements lasted for 48 hours, and all measurements were corrected for blank gas production (gas production in buffered rumen fluid without sample). After pressure readings, a small gas sample (2 ml) was taken from the headspace using a Hamilton gas tight syringe for immediate CH_4 analysis by gas chromatography (Agilent 490 Micro gas chromatograph). The gas chromatograph was equipped with a 10m stainless steel column packed with Porapak-Q and a Thermal Conductivity Detector (TCD). The injector temperature and column temperature was set at 45°C and 50°C respectively with a 30 ms injection time and a static pressure of 80 kPa.

Statistical analysis

The data collected were subjected to an analysis of variance (ANOVA) with factors: 4 blocks and 14 species. Differences were tested for significance between the three ecological groups and between species. The Shapiro-Wilk's test was performed on the standardized residuals to test for deviations from normality (Shapiro and Wilk, 1965). In cases where there were significant deviations from normality and it was due to skewness, outliers were removed until the distribution of the residuals were normal or symmetrical (Glass *et al.,* 1972). Student's t-LSD (least significant difference) was calculated at a 5% significance level to compare means of significant source effects. All data analysis was performed with SAS version 9.1.2 statistical software (SAS, 2004).

Results and discussion

Specie chemical composition

The chemical composition (% of DM) of the selected sub-tropical grass species is presented in Table 6.1. The ash concentration varied widely between species ranging from 4.35% for *U. agropyroides* to 10.53% of DM for *P. maximum* var. Gatton with an average across all selected species of 7.41% of DM. The ash concentration for sub-tropical grasses reported in Table 6.1 is comparable to values reported for sub-tropical grasses by Bredon *et al*. (1987), and Gemeda and Hassen (2014) who worked in similar geographical regions. The CP concentration (% of DM) ranged between 2.40% to 6.67% of DM with the highest CP concentration for *D. eriantha* and the lowest for *T. spicatus*. The mean CP concentration across all species was 4.14% of DM which is in the range of the value of 4.94% of DM reported by Singh *et al*. (2011) for a mixture of sub-tropical grasses used for livestock production in India and values reported by Bredon *et al*. (1987) for mixed rangeland types in South Africa during the late summer. All the species analysed had a CP concentration below 7 % which is the minimum CP concentration required for effective ruminal fermentation (Van Soest, 1994). Crude protein concentrations below this threshold will restrict ruminal microbial activity due to a lack of nitrogen (Hariadi and Santoso, 2010; Kulivand and Kafilzadeh, 2015).

The NDF concentration and digestibility of forages are important factors influencing efficient livestock feeding due to its direct effect on animal performance and variability in ruminal fermentation (Oba and Allen, 1999). The NDF concentration for grasses in the present study ranged from 64.70% to 73.77% of DM with ADF and ADL concentrations ranging from 43.97% to 49.55% and from 7.25% to 11% of DM respectively. *Eragrostis curvula*, *H. dissoluta* and *A. gayanus* had the highest values for NDF, ADF and ADL respectively. High

cell wall concentrations of forages will suppress ruminal microbial activity through a reduction in the availability of rapidly fermentable carbohydrates (Wilson and Hatfield, 1997) and it will have a negative effect on the voluntary dry matter intake (DMI) of grazing ruminants (Rafay *et al.*, 2013). Van Soest (1994) stated that the DMI of cattle will be negatively influenced when the NDF concentration of sub-tropical grasses increases above 60% of DM. Ninety-three percent of the species in the current study had a NDF concentration greater than 65%. The results reported in Table 6.1 are similar to results reported for fibre fractions of sub-tropical grasses by Rafay *et al*. (2013) and Gemeda and Hassen (2014). The low CP and high cell wall concentrations in the present study could be due to the advanced stage of maturity and the growing conditions under which the grasses were produced. As forages mature there is a decrease in the N concentration and digestibility with an increase in the fibre and lignin concentrations (Minson, 1990). Grasses produced at high temperatures and in low moisture soil produce material with high NDF and lignin concentrations (Bohn, 1990; Lee *et al.*, 2017). The advanced stage of maturity of the species sampled resulted in a leaf: stem ratio ranging from 0.64:1 (*T. spicatus*) to 3.7:1 (*H. contortus*) with an average across all species of 1.46:1 (data not reported). As grass plants mature the increase in DM yield and height is mainly due to stem elongation which is consistent with a reduction in leafiness (Ribeiro *et al.*, 2014). The hemicellulose and cellulose concentrations reported in Table 6.1 are comparable to figures reported by Singh *et al*. (2011) for sub-tropical dry forages with across specie means of 21.4% and 37.6%, respectively. The fibre fractions in the current study are slightly higher than results reported by Abdalla *et al*. (2012) for sub-tropical grasses. These differences may be due to differences in the climatic and soil conditions in which forages were grown between the two studies.

The IVOMD ranged from 22.47% to 42.2% of DM. These values are comparable to IVOMD values for sub-tropical grass species reported by Meale *et al*. (2012). The low IVOMD corresponds with the high ADF and lignin concentrations and the low CP concentrations reported for the selected species. The calculated ME concentration ranged from 3 to 5.7 MJ/ kg DM for *A. gayanus* and *U. agropyriodes* respectively (Table 6.1). These values are similar to data reported by Singh *et al*. (2011) of 5.5 MJ/ kg DM for dried mixed sub-tropical grass and reflects the low IVOMD reported in Table 6.1. The quality of all selected grass species in the present study can be categorized as low to poor according to the criteria reported by Meissner *et al*. (1999). The high NDF, low CP, IVOMD, and ME concentrations are consistent with mature sub-tropical grass species at the end of the growing season (O'Reagain and Mentis, 1990).

Table 6.1 Chemical composition of selected sub-tropical grass species (% of DM)

Species	Ash	CP	NDF	ADF	ADL	Cellulose	Hemi-cellulose	IVOMD	GE**	ME**	EE
A. gayanus	6.7_{cde}	3.2_{efgh}	68.5_{bc}	49.4_{a}	11.0_{a}	38.5_{abc}	19.1_{cd}	22.5_{f}	16.5_{ab}	3.0_{f}	1.0_{acde}
B. bladhii	7.4_{bcde}	3.4_{defgh}	64.7_{cd}	46.0_{abcd}	10.7_{a}	35.3_{c}	18.6_{cd}	26.1_{def}	16.4_{ab}	3.5_{ef}	0.9_{cdef}
C. ciliaris	7.3_{bcde}	4.9_{bcd}	70.5_{ab}	49.0_{a}	8.7_{bc}	40.4_{ab}	21.5_{bc}	34.0_{abcd}	16.1_{abcd}	4.4_{bcde}	1.1_{abcd}
C. excuvatus	7.2_{bcde}	3.1_{fgh}	66.0_{cd}	44.8_{bcd}	8.6_{bc}	36.3_{bc}	21.2_{bc}	33.1_{bcde}	16.6_{a}	4.4_{bcde}	1.5a
D. eriantha	9.0_{ab}	6.7_{a}	67.5_{bc}	45.9_{abcd}	9.9_{ab}	35.0_{c}	21.7_{bc}	40.3_{ab}	16.0_{bcd}	3.6_{def}	1.5_{ab}
E. curvula	5.6_{ef}	3.7_{defgh}	73.8_{a}	44.5_{cd}	8.3_{bc}	36.4_{bc}	29.3_{a}	25.3_{ef}	16.6_{a}	3.4_{ef}	0.9_{cdef}
E. miticus	6.4_{def}	4.0_{cdefgh}	67.9_{bc}	44.3_{cd}	8.6_{bc}	35.7_{c}	23.5_{b}	33.1_{bcde}	16.6_{a}	4.4_{bcde}	1.1_{abcde}
H. contortus	7.0_{bcde}	3.9_{cdefgh}	66.4_{bcd}	44.5_{cd}	8.4_{bc}	36.2_{bc}	21.9_{bc}	29.8_{cdef}	16.6_{ab}	4.0_{cdef}	0.6_{ef}
H. dissolute	8.3_{bcd}	4.5_{cdefg}	68.5_{bc}	49.5_{a}	9.2_{ab}	40.4_{ab}	18.9_{cd}	36.5_{abc}	15.8_{cde}	4.7_{abcd}	1.1_{abcde}
P. maximum	8.1_{bcd}	5.5_{abc}	66.9_{bcd}	47.4_{abcd}	9.5_{ab}	37.9_{abc}	19.5_{cd}	34.5_{abc}	16.7_{a}	5.0_{abc}	1.3_{abc}
P. maximum* var. *Gatton	10.5_{a}	6.3_{ab}	65.6_{cd}	44.0_{d}	8.4_{bc}	35.6_{c}	21.6_{bc}	40.5_{ab}	15.4_{e}	5.0_{abc}	1.2_{abcd}
S. megaphylla	9.0_{ab}	4.6_{cdef}	67.5_{bc}	48.6_{ab}	10.6_{a}	38.0_{abc}	19.0_{cd}	32.6_{bcde}	15.6_{de}	4.1_{bcdef}	1.0_{bcdef}
T. spicatus	6.3_{def}	2.4_{h}	67.0_{bcd}	48.1_{abc}	8.7_{bc}	39.4_{abc}	18.9_{cd}	23.2_{f}	16.3_{abc}	3.1_{f}	0.5_{f}
T. triandra	8.7_{abc}	3.0_{gh}	67.6_{bc}	45.6_{abcd}	8.5_{bc}	38.3_{abc}	22.03_{bc}	29.9_{cdef}	16.2_{abc}	3.9_{cdef}	0.8_{def}
U. agropyriodes	4.4_{f}	3.4_{defgh}	73.1_{a}	48.3_{abc}	7.3_{c}	41.1_{a}	24.8_{b}	42.2_{a}	16.5_{ab}	5.7_{a}	0.9_{cdef}
Overall mean	7.4	4.1	68.0	46.5	9.1	37.6	21.4	31.9	16.3	4.1	1.0
RMSE	1.3	0.9	2.6	2.4	1.0	2.5	2.3	4.8	0.3	0.6	0.3

Means within a column with different subscripts differ significantly ($P < 0.05$). DM: Dry matter; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; GE: Gross energy; ME: Metabolizable energy; EE: Ether extract; RMSE: Root mean square error.

** Units: MJ/ kg DM

Ecological group chemical composition

Rangeland condition can be defined in terms of ecological status, resistance to soil erosion and its potential to produce forage for sustained optimum livestock production (Trollope *et al.*, 1990). The ecological status of grasses is based on the classification of grass species according to their reaction to defoliation (Tainton, 1982). In the present study, there were differences ($P < 0.05$) between the CP concentration and IVOMD of Decreaser species and Increaser I and II species. Decreaser species had a higher ($P<0.05$) CP concentration and tended towards a higher IVOMD compared to Increaser I and II species (Table 6.2). Decreaser species also contained a higher ($P<0.05$) ash concentration compared to Increaser II species. These results suggest that rangeland dominated by Decreaser species should be of greater quality and have a greater potential for livestock production. O'Reagain and Mentis (1990) presented a study that showed that rangeland condition did not affect dietary quality in terms of CP or *in vitro* digestibility. These authors argued that any relationship between rangeland condition and rangeland quality will only likely be evident later during the grazing season when forage availability is restricted and the potential for livestock to select a higher quality diet is reduced as was mimicked in the present study. In contrast, Hardy and Mentis (1986) reported a significant relationship ($P<0.01$) between rangeland condition and diet quality when data from an entire growing season was analysed.

In vitro gas production, methane production and methane: total gas ratio

The data presented in Table 6.3 for the cumulative *in vitro* gas and methane production show differences ($P<0.05$) between grass species in terms of both total *in vitro* gas production and *in vitro* methane production. The differences in the volume of gas produced between the species at different incubation times were mainly due to differences in the fibre concentrations and digestibility between the species as reported in Table 6.1. *Cenchrus ciliaris*, *P. maximum* var. Gatton and *U. agropyriodes* produced the highest total gas volume after 24 hours of incubation with 103.1ml/g DM, 96.4ml/ g DM, and 93.1ml/g DM respectively. These species had high IVOMD and CP concentrations compared to the rest of the selected species except for *U. agropyriodes* which had a CP concentration below the group average. After 48 hour incubation the three species producing the highest total *in vitro* gas production were *C. ciliaris*, *C. excuvatus* and *P. maximum* var. Gatton with 162ml/g DM, 142.9ml/g DM and 140.7ml/g DM respectively. The differences in the ranking of species in terms of maximum gas production between incubation times may be due to differences in the rate of fermentation of the chemical constituents of the grasses (Gemeda and Hassen, 2014). The range for total gas production at both incubation periods are comparable to the gas production ranges reported by Gemeda and Hassen (2014) for sub-tropical grass species of 25 to 100ml/g DM and 52.5 to 155ml/g DM at 24 and 48 hours respectively. Meale *et al*. (2012) reported higher 24 hour total gas production values for two sub-tropical grass species (*A. gayanus* and *B. ruziziensis*) compared to the data presented in Table 6.3. These differences may be due to differences in quality between species and possible differences in the incubation technique employed by the researchers. Meale *et al*. (2012) reported higher CP and IVOMD values for the sub-tropical grass species compared to species selected in the present study.

In vitro methane production showed similar trends at both the incubation periods compared to the total *in vitro* gas production. The variation in methane production between grass species in the present study may be attributed to differences ($P<0.05$) in the fibre fraction, CP concentration and IVOMD between species as reported in Table 6.1. *Cenchrus ciliaris*, *U.*

agropyroides and *P. maximum* var. Gatton produced the highest *in vitro* methane (ml/g DM) across both the 24 and 48 hour incubation periods. *Andropogon gayanus* and *B. bladhii* consistently produced the lowest volume of *in vitro* methane (ml/g DM) at both the incubation periods. The data presented in Table 6.3 for methane production is similar to the range reported by Gemeda and Hassen (2014). When comparing the highest (*C. ciliaris*) and lowest (*A. gayanus*) *in vitro* methane producers as reported in Table 6.3, there are differences ($P<0.05$) between the CP, NDF, ADL and IVOMD of the two species ($P<0.05$). Similarly, it has been reported previously that methane production can be influenced by the concentration and nature of the cell wall constituents digested (Santoso *et al.*, 2003; Singh *et al.*, 2011; Gemeda and Hassen, 2014).

Table 6.2 Chemical composition of selected sub-tropical grass species (% of DM) according to ecological status classification

Ecological status	Ash	CP	NDF	ADF	ADL	Cellulose	Hemi-cellulose	IVOMD	GE**	ME**	EE
Decreaser	8.8$_{a}$	5.1 $_{a}$	67.1 $_{a}$	46.6 $_{a}$	9.4 $_{a}$	37.3 $_{ab}$	20.6 $_{b}$	34.1 $_{a}$	15.9 $_{b}$	4.4$_{a}$	1.1 $_{a}$
Increaser I	6.5 $_{b}$	3.3 $_{b}$	68.2 $_{a}$	47.6 $_{a}$	9.1 $_{a}$	38.5 $_{a}$	20.6$_{b}$	31.4 $_{ab}$	16.4 $_{a}$	4.1$_{a}$	0.9 $_{ab}$
Increaser II	6.4 $_{b}$	3.9 $_{b}$	69.0 $_{a}$	44.4 $_{b}$	8.4 $_{b}$	36.1 $_{b}$	24.6 $_{a}$	29.4 $_{b}$	16.6 $_{a}$	4$_{a}$	0.8 $_{b}$
Mean	7.4	4.1	68.0	46.5	9.1	37.6	21.4	31.9	16.3	4.2	1.0
RMSE	1.3	0.9	2.6	2.4	1.0	2.5	2.3	4.8	0.3	0.7	0.3

Means within a column with different subscripts differ significantly (P < 0.05). DM: Dry matter; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; GE: Gross energy; ME: Metabolizable energy; EE: Ether extract; RMSE: Root mean square error.

** Units: MJ/ kg DM

The ratio of *in vitro* methane (CH_4) to total gas production (TG) can be used as an indication of the efficiency of fermentability of grass species. Species with a lower *in vitro* methane to total gas production (CH_4:TG) have the potential to be utilized in livestock production systems to reduce enteric CH_4 emissions. In the present study, the CH_4:TG ratio varied from 0.025 to 0.075 at 24 hours incubation for *B. bladhii* and *C. ciliaris* respectively and increased to 0.065 to 0.110 with a mean of 0.085 after 48 hours incubation. *Eragrostis curvula*, *E. miticus*, and *P. maximum* had CH_4:TG ratios below the 48 hour mean and CP values > 3.5% of DM. These species, except for *E. miticus*, are known for improved livestock production, and had cellulose concentrations below the group average (37.6% DM) and hemicellulose above the group average (21.4% of DM). The reason for the reduced CH_4: TG ratio is not clear as Holter and Young (1992) reported a positive and a negative relationship between CH_4 production and hemicellulose and cellulose digestibility respectively. *Cenchrus ciliaris* consistently produced the highest *in vitro* total gas, *in vitro* methane as well as the highest CH_4:TG ratio for both the incubation periods. This could partly be explained by the high NDF (70.5% of DM), ADF (49.0% of DM), and cellulose (40.4% of DM) concentrations of *C. ciliaris* in the present study. The low methanogenic potential of *A. gayanus* and *B. bladhii* reported in Table 6.3 is misleading as the low methanogenic potential could be due to a lower overall digestibility as reported in Table 6.1.

Table 6.3 Cumulative *in vitro* gas and methane production of selected sub-tropical grass species (ml/g DM)

	Total gas		Total CH_4		Methane: Total gas ratio	
Species	**24 Hour**	**48 Hour**	**24 Hour**	**48 Hour**	**24 Hour**	**48 Hour**
A. gayanus	59.57_{f}	89.95_{f}	1.96_{de}	5.98_{e}	0.033_{ef}	0.065_{g}
B. bladhii	54.27_{f}	92.79_{ef}	1.40_{e}	6.08_{e}	0.025_{f}	0.065_{g}
C. ciliaris	103.07_{a}	161.91_{a}	7.78_{a}	17.50_{a}	0.075_{a}	0.108_{a}
C. excuvatus	83.10_{abcd}	142.88_{ab}	4.40_{bcd}	12.65_{bc}	0.053_{bcde}	0.089_{bcdef}
D. eriantha	85.89_{abc}	120.30_{bcdef}	5.27_{abc}	11.10_{bcd}	0.06_{abc}	0.092_{bcde}
E. curvula	60.62_{ef}	103.76_{def}	2.23_{de}	8.27_{de}	0.036_{def}	0.079_{efg}
E. miticus	61.68_{def}	111.79_{bcdef}	4.06_{bcde}	9.27_{cde}	0.045_{bcdef}	0.081_{def}
H. contortus	69.73_{cdef}	124.65_{bcde}	3.30_{cde}	11.38_{bcd}	0.043_{cdef}	0.089_{bcdef}
H. dissolute	85.43_{abc}	136.70_{abc}	4.76_{bcd}	13.22_{bc}	0.056_{abcd}	0.097_{abc}
P. maximum	58.39_{f}	103.43_{def}	2.30_{de}	8.18_{de}	0.039_{def}	0.079_{efg}
P. maximum var. Gatton	96.36_{a}	140.71_{abc}	6.20_{ab}	13.33_{bc}	0.064_{abc}	0.094_{abcd}
S. megaphylla	72.29_{bcdef}	128.42_{bcd}	3.28_{cde}	11.08_{bcd}	0.044_{bcdef}	0.086_{bcdef}
T. spicatus	58.42_{f}	109.75_{cdef}	2.05_{de}	8.42_{de}	0.035_{def}	0.077_{fg}
T. triandra	81.51_{abcde}	132.90_{abcd}	3.89_{bcde}	11.36_{bcd}	0.045_{bcdef}	0.085_{cdef}
U. agropyriodes	93.10_{ab}	138.81_{abc}	6.07_{abc}	14.05_{ab}	0.065_{ab}	0.100_{ab}
Overall mean	74.92	122.43	3.93	10.78	0.048	0.085
RMSE	11.26	17.10	1.51	2.18	0.011	0.008

Means within a column with different subscripts differ significantly ($P < 0.05$); RMSE: Root mean square error; CH_4: Methane production

Ecological group in vitro gas and methane production and methane: total gas ratio

The differences (P<0.05) between the ADF and ADL concentrations of Increaser I and Increaser II specie groups did not materialise into differences (P>0.05) between the total *in vitro* gas, *in vitro* methane as well as the CH_4:TG ratio at both the 24 and 48 hour incubation periods (Table 6.4). The Decreaser specie group yielded consistently higher (P<0.05) total *in vitro* gas production, *in vitro* methane production and a higher CH_4:TG ratio compared to the Increaser specie groups. These differences in *in vitro* gas and methane production between the ecological groups could partly be explained by the higher (P<0.05) CP concentration of the Decreaser specie group as reported in Table 6.2. The higher quality of the Decreaser species should improve the efficiency of livestock production compared to Increaser I and Increaser II species and reduce the methane emissions per unit of product produced.

Table 6.4 Cumulative *in vitro* gas and methane production of selected sub-tropical grass species (ml/g DM) according to ecological status classification

Ecological status	TG		CH_4		CH_4:TG	
	24 Hour	48 Hour	24 Hour	48 Hour	24 Hour	48 Hour
Decreaser	79.80_a	133.76_a	4.98_a	12.47_a	0.056_a	0.092_a
Increaser I	75.93_b	114.60_b	3.18_b	9.49_b	0.042_b	0.080_b
Increaser II	65.44_b	115.72_b	3.32_b	9.99_b	0.042_b	0.084_b
Overall mean	74.92	122.43	3.93	10.78	0.048	0.085
RMSE	11.26	17.10	1.51	2.18	0.011	0.008

Means within a column with different subscripts differ significantly (P < 0.05). TG: Total *in vitro* gas production; CH_4: methane production; RMSE: Root mean square error.

Conclusion

The results in the present study demonstrate variation in *in vitro* methane production between sub-tropical grass species typical of transitional rangeland areas in South Africa. The variation between species allows for the potential to identify and select species with a lower enteric methane production potential. Producers should be cautious when selecting forages purely on methanogenic potential as a low methanogenic potential could be directly associated with low overall fermentability and hence digestibility. *Panicum maximum*, *E. curvula* and *E. miticus* were the three species which produced the lowest *in vitro* methane production but which also had a CP concentration of more than 3.5% of DM and with an IVOMD concentration above the group average for the study. *Cenchrus ciliaris* was the highest and *A. gayanus* as well as *B. bladhii* were the lowest *in vitro* methane producing species, respectively. Further, the present study revealed that *in vitro* methane production was higher in decreaser species compared to increaser species. There is a need for further assessment of the quality and fermentation characteristics of these species at various stages of maturity and across multiple seasons. *In vivo* research is needed to confirm the sustained mitigation potential as well as production capabilities of promising sub-tropical grass species identified in the present study.

Acknowledgements

This study forms part of a larger project jointly funded by the Red Meat Research and Development Trust of South Africa and the National Research Foundation of South Africa. The Animal Ethics Committee of the University of Pretoria approved all experimental protocols (ECO18-14) before commencement of the study.

References

Abdalla, A.L., Solton, Y.A., Silva, R.F., Louvandini, H., McManus, C.M., Lucas, R.C., Morsy, A.S., Beleosoff, B.S. and Abdalla Filho, A.L., 2012. Good quality grass pasture decreases rumen methane production *in vitro*. In: Proceedings "Visions for a sustainable planet". ASA, CSSA and SSSA International Annual Meetings, Oct 21 – 24, 2012. Cincinnati, Ohio.

Acocks, J.P.H., 1975. Veld types of South Africa (2nd ed.). Memoirs of the Botanical Survey of South Africa. No 40. Government printer, Pretoria, South Africa.

AOAC., 2000. Official methods of Analysis, 17t ed. Association of Official Analytical Chemists, Arlington, VA, USA.

Bannink, B.K., Durmic, Z., Erskine, W., Ghamkar, K. and Revell, C., 2013. *In vitro* ruminal fermentation characteristics and methane production differ in selected key pasture species in Australia. Crop and Past. Sci. 64, 935 – 942.

Beauchemin, K.A., McAllister, T.A. and McGinn, S.M., 2009. Dietary mitigation of enteric methane from cattle. CAB Review: Perspect. Agric. Vet. Sci. Nutr. Nat. Res. 4, 1 – 18.

Bezabih, M., Pellikaan, W.F., Tolera, A., Khan, N.A. and Hendriks, W.H., 2013. Chemical composition and *in vitro* total gas and methane production of forage species from the Mid Rift Valley grasslands of Ethiopia. Grass and Forage Sci. 69 (4), 1 – 9.

Bodas, R., Lopez, S., Fernandez, M., Garcia-Gonzalez, R., Rodriguez, A.B., Wallace, R.J. and Gonzalez, J.S., 2008. *In vitro* screening of potential of numerous plant species as antimethanogenic feed additives for ruminants. Anim. Feed Sci. Technol. 145, 245 – 258.

Bohn, P.J., 1990. Investigation in to the effect of phenolic acids on forage digestibility. Sci. Eng. 50, 4282 – 4283.

Bredon, R.M., Stewart, P.G. and Dugmore, T.J., 1987. 'A manual on the nutritive value and chemical composition of commonly used South African farm feeds.' Natal region, Department of Agriculture and Water Affairs, South Africa: Pretoria, South Africa.

De Waal. H.O., 1990. Animal production from native pasture (veld) in the Free State region– A perspective of the grazing ruminant. S. Afr. J. Anim. Sci. 20(1), 1 – 9.

Doreau, M., Benhissi, H., Thior, Y.E., Bois, B., Leydet, C., Genestoux, L., Lecomte, P., Morgavi, D.P. and Ickowicz, A., 2016. Methanogenic potential of forages consumed throughout the year by cattle in a Sahelian pastoral area. Anim. Prod. Sci. 56 (3), 613 – 618.

Du Toit, C.J.L., Meissner, H.H. and Van Niekerk, W.A., 2013a. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43(3), 320 – 339.

Du Toit, C.J.L., Meissner, H.H. and Van Niekerk, W.A., 2013b. Direct greenhouse gas emissions of the game industry in South Africa. S. Afr. J. Anim. Sci. 43 (3), 376 – 393.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013c. Direct greenhouse gas emissions of the South African small stock sectors. S. Afr. J. Anim. Sci. 43 (3), 340 – 361.

Durmic, Z., Hutton, P., Revell, D., Emms, J., Huges, S. and Vercoe, P., 2010. *In vitro* fermentation traits of Australian woody perennial plant species that may be considered as potential sources of feed for grazing ruminants. Anim. Feed Sci. Technol. 160, 98 – 109.

Durmic, Z., Moate, P.J., Jacobs, J.C., Vadhanabhuti, J. and Vercoe, P.E., 2016. *In vitro* fermentability and methane production of some alternative forages in Australia. Anim. Feed Sci. Technol. 56, 641 – 645.

Eckard, R.J., Grainger, C. and De Klein, C.A.M., 2010. Options for abatement of methane and nitrous oxide from ruminant production. Livest. Prod. Sci. 130, 47 – 56.

Gemeda, B.S. and Hassen, A., 2014. *In vitro* fermentation, digestibility and methane production of tropical perennial grass species. Crop and Past. Sci. 65, 479 – 488.

Getachew, G., Robinson, P.H., De Peters, E.J., Taylor, S.J., Gisi, D.D., Higginbotham, G.E. and Riordan, T.J., 2005. Methane production from commercial dairy rations estimated using *in vitro* gas technique. Anim. Feed Sci. Technol. 123-124, 391 – 402.

Glass, G.V., Peckham, P.D. and Sanders, J.R., 1972. Consequences of failure to meet assumptions underlying the fixed effects of variance and covariance. Rev. Educ. Res. 42 (3), 237 – 288.

Goel, G. and Makkar, H.P.S., 2012. Methane mitigation from ruminants using tannins and saponins, a status review. Trop. Anim. Health and Prod. 44, 729 – 729.

Goering H.K. and Van Soest P.J., 1970. Forage fiber analyses. (Apparatus, reagents, procedures, and some applications). USDA Agricultural Handbook no. 379, Pg. 1 – 20. ARS/USDA, Washington, D.C.

Hackmann, T.J., Sampson, J.D. and Spain, J.N., 2008. Comparing relative feed value with degradation parameters of grass and legume forages. J. Anim. Sci. 86,2344 – 2356.

Hardy, M.B. and Mentis, M.T., 1986. Grazing dynamics in sour grassveld. S. Afr. J. Anim. Sci. 82, 566 – 572.

Hardy, M.B., Hurt, G.R. and Bosch, J.H., 1999. Veld condition assessment. In: Veld management in South Africa, Ed. N. M Tainton. University of Natal Press, Pietermaritzburg, South Africa.

Hariadi, B.T. and Santoso, B., 2010. Evaluation of tropical plants containing tannin on *in vitro* methanogenesis and fermentation parameters using rumen fluid. J. Sci. Food and Agric. 90 (3), 456 – 461.

Holter, J.B. and Young, A.J., 1992. Methane prediction in dry and lactating Holstein cows. J. Dairy Sci. 75 (8), 2165 – 2175.

Kottet, M., Griese, J., Beck, C., Rudolf, B. and Rubel, F., 2006. World map of the Köppen-Gieger climate classification – updated. Meteorologische Zeitschrift 15 (3), 259 – 263.

Kulivand, M. and Kafilzadeh, F., 2015. Correlation between chemical composition, kinetics of fermentation and methane production of eight pasture grasses. Acta Scientia. Anim. Sci. 37 (1), 9 – 14.

Lee, A.M., Davis, A.P., Chagunda, M.G.G. and Manning, P., 2017. Forage quality declines with rising temperatature, with implications for livestock production and methane emissions. Biogeosciences 14, 1403 – 1412.

Meale, S.J., Chaves, A.V., Baah, J. and McAllister, T.A., 2012. Methane production of different forages in *in vitro* ruminal fermentation. Asian-Aust. J. Anim. Sci. 25 (1), 86 – 91.

Meissner, H.H., Scholtz, M.M. and Engelbrecht, F.C., 2013. Sustainability of the South African livestock sector towards 2050. Part 2: Challenges, changes and required implementations. S. Afr. J. Anim. Sci. 43 (3), 298 – 319.

Meissner, H.H., Zacharias, P.J.K., and O'Reagain, P.J. 1999. Forage quality In: Veld management in South Africa. Ed. N.M Tainton. University of Natal Press, Pietermaritzburg.

Menke, K.H. and Steingass, H., 1988. Estimation of the energetic feed value obtained from chemical analysis and *in vitro* gas production using rumen fluid. Anim. Res. Develop. 28, 7 – 55.

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E. and France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. J. Anim. Sci. 81, 3141 – 3150.

Minson, D.J., 1979. Relationships of conventional and preferred fractions to determine energy values. Proc. Workshop on analytical methods. Ottawa

Minson, D.J., 1990. Forage in ruminant nutrition, Academic press, London.

Moe, P.W., and Tyrrell, H.F. (1979). Methane production from dairy cows. J. Dairy Sci. 62, 1583 – 1586.

Mould, F.L., Morgan, R., Kliem, K.E. and Krystallidou, E., 2005. A review and simplification of the *in vitro* incubation medium. Anim. Feed Sci. Technol. 123, 155 – 172.

O'Reagain, P.J. and Mentis, M.T., 1990. The effect of veld condition on the quality of diet selected by cattle grazing the Natal sour sandveld. J. Grassland Soc. S. Afr. 7 (3), 190 – 195.

Oba, M. and Allen, M.A., 1999. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: Effects on dry matter intake and milk yield in dairy cows. J. Dairy Sci. 82, 589 – 586.

Rafay, M., Khan, R.A., Yaqoob, S. and Ahmad, M., 2013. Nutritional evaluation of major range grasses from Cholistan desert. Pak. J. Nutr. 12(1), 23 – 29.

Ribeiro, G.O. Jr., Teireira, A.M., Velasco, F.O., Faris Junior, W.G., Pereira, L.G., Chaves, A.V., Gonçalves, L.C. and McAllister, T.M., 2014. Production, nutritional quality and *in vitro* methane production from *Andropogon gayanus* grass harvested at different maturities and preserved as hay or silage. Asian-Aust. J. Anim. Sci. 27(3), 330 – 341.

Robinson, P.H., Givens, D.I. and Getachew, G., 2004. Evaluation of NRC, UC Davis and ADAS approaches to estimate the metabolizable energy values of feeds at maintenance energy intake from equations utilizing chemical essays and *in vitro* determinations. Anim. Feed Sci. Technol. 114 (1– 4), 75 – 90.

Santoso, B., Kume, S., Nonaka, K., Kimura, K., Mizokoshi, H., Gamo, Y. and Takahashi, J., 2003. Methane emission, nutrient digestibility, energy metabolism and blood metabolites in dairy cows fed silages with and without galacto-oligosacharides supplementation. Asian-Aust. J. Anim. Sci. 16, 534 – 540.

SAS., 2004. The statistical procedure manual, Version 9.1.2. North Carolina 27513: SASCampus drive, Cary, NC, USA.

Shapiro, S.S. and Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591 – 611.

Singh, S., Kushwaha, B.P., Nag, S.K., Mishra, A.K., Bhattacharya, S., Gupta, P.K. and Singh, A., 2011. *In vitro* methane emissions from Indian dry roughages in relation to chemical composition. Current Sci. 101(1), 57 – 65.

Tainton, N.M., 1982. Veld evaluation and sweetveld observation. Proc. Beef and game on sweetveld symposium, October 1982. Hlabisa Soil Conservation Committee: 24 – 30.

Theodorou M.K., Williams B.A., Dhanoa M.S., McAllen A.B. and France J., 1994. A simple gas production method using pressure transducers to determine the fermentation kinetics of ruminant feed. Anim. Feed Sci. Technol. 48, 185-197.

Trollope, W.S.W., Trollope, L.A. and Bosch, O.J.H., 1990. Veld and pasture management terminology in South Africa. J. Grassland Soc. S. Afr. 7, 52 – 61.

Van Soest, P.J., 1994. Nutritional ecology of ruminants. Ithaca, NY: Cornell University Press.

Vorster, M., 1982. The development of the Ecological Index Method for assessing veld condition in the Karoo. Proceedings of the Grassland Society of South Africa 17, 84 – 89.

Wilson, J.R. and Hatfield, R.D., 1997. Structural and chemical changes of cell wall types during stem development: consequences for fiber degradation by rumen microflora. Aust. J. Agric. Res. 48, 165 – 180.

Chapter 7

In vitro total and methane gas production of common South African improved sub-tropical and temperate grass species as influenced by nitrogen fertilization.

C.J.L du Toit[1,2#], W.A. van Niekerk[2], H.H. Meissner[3], L.J. Erasmus[2] and L Morey[4]
[1]Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa
[2]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[3]No 3 Die Hoewes, 276 von Willich Street, Centurion, 0157, South Africa
[4]ARC-Biomerty, ARC-Central Office, 1134 Park Street, Hatfield, 0087, South Africa
[#]Corresponding author: dutoitcjl@tut.ac.za; Tel: +27123824292; Fax: +27123825220

Abstract

The aim of the study was to evaluate the effect of level of nitrogen (N) fertilization on certain qualitative parameters and *in vitro* total gas and methane production of improved grass species commonly used in South Africa. Treatments included seven grass species divided into two photosynthetic pathways (C3 and C4) with three levels of nitrogen fertilization (0, 50 and 100 kg N/ha). Plants were grown in a greenhouse and nitrogen was applied in a single application after a simulated defoliation. Sample material was harvested by hand after an 8 week regrowth period. Both grass species and rate of nitrogen fertiliser had significant ($P < 0.05$) effects on the nutritive value and *in vitro* organic matter digestibility of the selected species. No effect was found for nitrogen fertilization on *in vitro* total gas or methane production in the trial. The crude protein concentration increased and the NDF concentration tended to decrease as the rate of nitrogen fertilization increased for both C3 and C4 species. Increasing the rate of nitrogen fertiliser increased ($P < 0.05$) the methanogenic potential of *D. glomorata*, *F. arundinacea* and *C. ciliaris* after the 24 hour incubation period but no significant effects was reported after the 48 hour incubation period. The present data suggests that the stage of physiological development of forages might have a greater influence on the methanogenic potential of forages compared to the effect of nitrogen fertiliser application.

Key words: greenhouse gases, fermentation, digestibility, nutritive value

Introduction

Understanding the effect of forage quality on the production of anthropogenic greenhouse gases from livestock is important for the development of mitigation strategies for agricultural systems. The livestock sector is a significant source of greenhouse gas (GHG) emissions in South Africa contributing 60% of total agricultural CO_2 equivalent emissions (Meissner *et al.,* 2013). Beef cattle, sheep and privately owned game rely mainly on extensive forage-based production systems

and accounts for 85% of total livestock methane emissions in South Africa (Du Toit *et al.*, 2013a,b,c).

The productivity of ruminant livestock in tropical and sub-tropical regions are limited by poor nutritional conditions characterised by highly lignified, low digestible feed from poor and often nitrogen (N) limited native rangeland and crop residues (Goel and Makkar, 2012). Improving forage quality through selection, rangeland reinforcement and improved management systems has the potential to reduce CH_4 emissions per unit animal product as a result of increased digestibility and reduced ruminal retention time of feed particles (Beauchemin *et al.*, 2009; *Bannink et al.*, 2013). Benchaar *et al.* (2014) stated that a 15 % reduction in methane emissions could be possible by increasing the digestibility of forages and a 7% reduction through increasing of voluntary feed intake of livestock.

Studies evaluating the effect of N fertilization on the methanogenic potential of tropical and sub-tropical pastures are rarely available. Nitrogen fertilization can influence the pattern of degradation in the rumen of crude protein (CP) and neutral detergent fibre (NDF) (Valk *et al.*, 1996) which could influence the methanogenic potential of forages. *In vitro* techniques have been used by several researchers as a practical screening tool to predict plant digestibility, fermentation characteristics and methanogenic potential taking into consideration the complex interaction between rumen microbes and feed particals (Lovett *et al.*, 2006; Durmic *et al.*, 2010; *Bannink et al.*, 2013).

The aim of this study was to evaluate the influence of a range of nitrogen fertilizer application rates on the nutrient concentration, *in vitro* organic matter digestibility, *in vitro* total gas production and *in vitro* methanogenic potential of commonly used improved sub-tropical (C4) and temperate (C3) grass species in South Africa. Variability in these traits among accepted improved pasture species would allow for the selection of low methanogenic pastures that do not compromise animal productivity. This would improve the ability of producers to reduce methane emissions from livestock, reducing the carbon foot print of production systems, without major changes in current production practices.

Material and Methods

Study area description

The experiment was conducted in a glass greenhouse situated on the Hatfield experimental farm of the University of Pretoria, South Africa. Seven grass species of current economic importance in South Africa were investigated (Table 7.1) in two groups. Four species in the C4 group and three species in the C3 group. The effect of three nitrogen (N) levels were evaluated: 0, 50, and 100 kg N ha^{-1}. All treatments were replicated three times in a randomized complete block design. Seeds were sourced from a commercial company and sown into 10 L pots in a controlled environment where the temperature and humidity varied between 18 -34°C and 30 – 68%, respectively. The pots were filled with 12 kg of an air dried and sieved potting soil mixture comprising of 20% clay, 23% silt and 57% sand. Soil samples were analysed at a commercial accredited laboratory. Some physical and chemical characteristics of the soil were: a bulk density of 1.1 g/ cm^3; 300 mg/ kg P (Bray I); 2554 mg/ kg K; 556 mg/ kg Na; 3650 mg/ Kg Ca; 616 mg/ kg Mg; and a pH (KCL) of 5.63.

Ten seeds from each specie were planted per pot and allowed to germinate. Once established, the

seedlings were thinned out to three uniform seedlings per pot. All pots received a single dressing of nitrogen fertilizer, as limestone ammonium nitrate (LAN, 28%N) after the thinning process according to the experimental treatments. The pots were rotated once a week in the glasshouse to minimize the influence of environmental variation within the glasshouse. All pots were weighed and watered to 90% field capacity according to Pieterse *et al.* (1997). To prevent mineral loss all pots received a saucer and any leached water was returned to the pots an hour after watering. For the remainder of the trial period, the pots were weighed every three days and watered to 90% field capacity.

Samples for the analysis of nutritive value and *in vitro* fermentation were obtained from the second regrowth phase after an initial harvesting cycle. All species were harvested at 5cm above soil level by hand after a 8 week regrowth period. The harvested material was air dried and ground to pass through a 1.0 mm screen. Material was stored at room temperature (20 - 25°C) in sealed containers for analysis.

Table 7.1 List of perennial grass species investigated including common and scientific names, cultivar, and photosynthetic pathway

Common name	Scientific name	Cultivar	Photosynthetic pathway
Blue buffalo grass	*Cenchrus ciliaris*	cv. Molopo	C4
Rhodes Grass	*Chloris gayana*	cv. Katambora	C4
Smuts Finger grass	*Digitaria eriantha*	cv. Irene	C4
Buffalo grass	*Panicum maximum*	cv. Gatton	C4
Cocksfoot	*Dactylis glomorata*	cv. Cambria	C3
Tall fescue	*Festuca arundinacea*	cv. Duramax	C3
Perennial ryegrass	*Lolium perenne*	cv. Halo	C3

Nutritive value

Plant samples were analysed for dry matter (DM), organic matter (OM), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), *in vitro* organic matter digestibility (IVOMD) and metabolizable energy (ME). The DM content was determined by drying samples for 24 h at 105°C in a forced air oven after which the samples were combusted at 450°C for 8 h in a muffle furnace to determine the OM concentration (AOAC, 2000). Nitrogen (N) concentration of samples were analysed by total combustion (AOAC, 2000) on a LECO FP-248 Nitrogen and Protein analyser (LECO corporation, St Joseph, MI, USA). The NDF and ADF contents were determined using an ANKOM 200/220 Fibre Analyser (ANKOM Technology, Fairport, NY, USA) based on the methods described by Van Soest *et al.* (1991). Sodium sulphite and heat stable amylase were used in the analysis of NDF. The lignin concentration (ADL) was determined according to Van Soest *et al.* (1991) through the solubilisation of cellulose with sulfuric acid in the ADF residue. The NDF was expressed inclusive of residual ash. Metabolizable energy (ME) was calculated from gross energy (GE) and *in vitro* organic matter digestibility

according to Minson (1979) and Robinson *et al.* (2004) as ME (MJ/kg DM) = 0.81[(GE x IVOMD) / 100].

In vitro digestibility, total gas, and methane production measurement

In vitro organic matter digestibility was determined using the Tilley and Terry method (Tilley and Terry, 1963) as modified by Engels and Van der Merwe (1967). Three rumen cannulated Döhne Merino wethers were used as rumen inoculum donors. The care, handling and maintenance of cannulated sheep were in accordance with animal welfare regulations of the animal ethics committee of the University of Pretoria (EC018-14). The donor sheep were kept on a diet consisting of 50% *Eragrostis curvula* hay and 50% *Medicago sativa* hay. Rumen fluid was collected two hours after the morning feeding, pooled, and filtered through two layers of cheese cloth. The rumen fluid was stored in a pre-warmed insulated thermos flask pre-filled with CO_2.

Samples for gas analysis were incubated in triplicate according to the procedure described by Theodorou *et al.* (1994). Approximately 400 mg of sample was weighed into 120 ml serum bottles. Filtered rumen fluid (15 ml) was mixed (1:2, v/v) with an anaerobic buffer/ mineral solution prepared according to Goering and Van Soest (1988) with modifications suggested by Mould *et al.* (2005). After saturation with CO_2 the serum bottles were sealed with rubber stoppers and aluminum crimp seal caps. Possible gas build up was equalized by inserting a hypodermic needle through the rubber stopper for approximately 5 seconds. Thereafter the sample bottles were placed in an incubator at 39°C with a rotary shaker set at 120 rpm. The incubation and gas production measurements lasted for 48 hours, and all measurements were corrected for blank gas production (gas production in buffered rumen fluid without sample). The system consisted of a digital data logger (tracker 220 series indicators, Omega Engineering, Inc., Laval, QC, Canada) connected to a pressure transducer (PX4200-015GI from Omega Engineering, Inc., Laval, QC, Canada). Gas pressure was measured at 0, 4, 12, 24, and 48 hour time intervals using the pressure transducer. After each pressure reading a small gas sample (2 ml) was taken from the headspace using a Hamilton gas tight syringe for immediate CH_4 analysis by gas chromatography (Agilent 490 Micro gas chromatograph). The gas chromatograph was equipped with a 10m stainless steel Porapak-Q column and a Thermal Conductivity Detector (TCD). The injector temperature and column temperature was set at 45°C and 50°C respectively with a 30 ms injection time and a static pressure of 80 kPa. Methane content (ml g^{-1} DM incubated) was calculated according to *Bannink et al.* (2013).

Statistical analysis

The two groups of grass species (3 species in the C3 group and 4 in the C4 group) were analysed separately. The data were subjected to an analysis of variance (ANOVA) with 2 factors and 3 block replications using the GLM procedure in SAS (SAS, 1999). The Shapiro-Wilk's test was performed on the standardized residuals to test for deviations from normality (Shapiro and Wilk, 1965). In cases where there were significant deviations from normality and it was due to skewness, outliers were removed until the distribution of the residuals were normal or symmetrical (Glass *et al.*, 1972). Student's t-LSD (Least significant difference) was calculated at a 5% significance level to compare means of significant source effects.

Results

Both grass species and rate of nitrogen fertilization had significant ($P < 0.05$) effects on the nutritive value, *in vitro* organic matter digestibility and the *in vitro* gas production characteristics of the selected grass species (Table 7.2 and 7.3). Interactions between grass specie and N fertilization rate were significant for NDF and ADF in tropical (C4) grass species (Table 7.2) and for IVOMD in temperate (C3) grass species (Table 7.3).

The rate of N fertilization had no effect ($P > 0.05$) on the *in vitro* gas production parameters except for the 24 hour CH_4 production of temperate grass species (Table 7.3). *In vitro* gas production was not effected by interactions between grass specie and the rate of N fertilization in both tropical or temperate grass species.

Forage quality

The nutritive analysis of the grass species indicated that N fertilization decreased the ash and NDF concentration of both C4 and C3 grass species (Table 7.4 and 7.5). Although no effect was shown in the ADF and ADL concentration of C3 species, the ADF concentration of C4 species tended to decrease with increased fertilization rate. The CP concentration increased with the rate of N fertilization across all the species. *In vitro* organic matter digestibility increased in *C. ciliaris* and *D. eriantha* (Table 7.4) but decreased in *D. glomorata* (Table 7.5) as the rate of N fertilization was increased from 0 to 100 kg N ha^{-1}.

Table 7.2 Analysis of variance for forage quality factors (DM basis) for tropical (C4) grass species

Parameters	Sp	N	Sp x N	R^2	CV	Mean
Ash (%)	<0.001	0.119	0.190	0.81	7.05	11.60
CP (%)	<0.001	<0.001	0.881	0.76	11.50	7.09
NDF (%)	<0.001	0.002	<0.001	0.96	1.63	64.94
ADF (%)	<0.001	<0.001	0.017	0.94	2.38	36.23
ADL (%)	<0.001	0.504	0.676	0.72	12.26	4.70
IVOMD (%)	<0.001	<0.001	0.065	0.94	4.54	58.21
ME (MJ/kg.DM^{-1})	<0.001	0.046	0.086	0.75	8.23	7.67
TGP 24 h (ml/g.DM^{-1})	0.002	0.816	0.443	0.55	12.63	96.70
CH_4 24 h (ml/g.DM^{-1})	<0.001	0.459	0.318	0.69	12.99	4.16
TGP 48 h (ml/g.DM^{-1})	0.019	0.560	0.424	0.48	5.56	150.34
CH_4 48 h (ml/g.DM^{-1})	0.018	0.725	0.663	0.48	11.69	10.37

Sp: Specie; N: N kg ha^{-1}; Sp x N: Specie x N kg ha^{-1}; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; ME: Metabolizable energy; TGP: Total gas production; CH_4: *In vitro* methane production.
A probability $P<0.05$ is considered as significant and $P<0.01$ as highly significant

Table 7.3 Analysis of variance for forage quality factors (DM basis) for temperate (C3) grass species

Parameters	Sp	N	Sp x N	R^2	CV	Mean
Ash (%)	<0.001	0.182	0.122	0.77	6.97	14.36
CP (%)	0.036	<0.001	0.379	0.90	8.16	9.87
NDF (%)	<0.001	0.126	0.315	0.75	3.30	54.66
ADF (%)	<0.001	0.408	0.095	0.87	4.26	31.40
ADL (%)	0.034	0.118	0.334	0.56	14.86	3.72
IVOMD (%)	<0.001	<0.001	<0.001	0.97	3.03	72.07
ME (MJ kg DM^{-1})	0.007	0.460	0.846	0.58	12.12	11.67
TGP 24 h (ml g DM^{-1})	<0.001	0.149	0.327	0.77	10.96	113.10
CH_4 24 h (ml g DM^{-1})	<0.001	0.018	0.089	0.75	15.48	4.81
TGP 48 h (ml g DM^{-1})	<0.001	0.367	0.404	0.77	7.64	158.79
CH_4 48 h (ml g DM^{-1})	<0.001	0.163	0.406	0.87	9.30	9.60

Sp: Specie; N: N kg ha^{-1}; Sp x N: Specie x N kg ha^{-1}; NS: Not significant
CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; ME: Metabolizable energy; TGP: Total gas production; CH_4: *In vitro* methane production
A probability P<0.05 is considered as significant and P<0.01 as highly significant

Metabolizable energy concentration was not effected by the rate of N fertilization in both C4 or C3 grass species although between specie differences were present across all fertilization rates for C4 species and at the 100 kg N ha^{-1} treatment for C3 species. *Cenchrus ciliaris* had lower ($P < 0.05$) CP concentrations across all fertilization treatments compared to *D. eriantha* and *P. maximum*. *Digitaria eriantha* had the highest CP concentration at the 0 and 50 kg N ha^{-1} treatments with 7.16% and 8.37%, respectively and *P. maximum* had the highest CP concentration at the 100 kg N ha^{-1} treatment with 8.7% (Table 7.4). Both *D. eriantha* and *P. maximum* had lower ($P < 0.05$) NDF concentrations compared to *C. ciliaris* and *C. gayana*. The highest ADF ($P < 0.05$) and ADL ($P < 0.05$) concentrations were reported for *C. ciliaris* with the highest IVOMD ($P < 0.05$) across all N treatments reported for *P. maximum* compared to the other C4 species investigated.

The nutritive concentration from temperate, C3, species is presented in Table 7.5. There was less between species variation in the C3 species compared to the C4 species investigated in the trial. No differences were found for CP at the 0 and 50 kg N ha^{-1} treatments between C3 species but *L. perenne* had the highest CP concentration ($P < 0.05$) compared to *D. glomorata* and *F. arundinacea* at the 100 kg N ha^{-1} treatment. *Dactylis glomorata* had a higher NDF concentration ($P < 0.05$) across the different fertilization treatments compared to *F. arundinacea* and *L. perenne*. The lowest ADF ($P < 0.05$) concentrations were reported for *F. arundinacea* and the highest IVOMD ($P < 0.05$) for *L. perenne* in all the fertilization treatments compared to other C3 species investigated (Table 7.5).

Table 7.4 Effect of nitrogen fertilization on the chemical composition (% of DM) of improved tropical C4 grass species commonly used in South Africa

	N kg/ ha	Ash	CP	NDF	ADF	ADL	IVOMD	ME
C. ciliaris	0	10.58^{fg}	5.16^{f}	68.09^{bc}	40.49^{b}	5.78^{a}	60.15^{b}	8.26^{abc}
	50	9.66^{gh}	5.56^{ef}	73.04^{a}	42.82^{a}	5.74^{a}	58.14^{bc}	7.62^{bcde}
	100	8.95^{h}	6.58^{cde}	67.54^{bc}	40.70^{b}	5.89^{a}	66.29^{a}	8.73^{ab}
C. gayana	0	13.07^{ab}	6.00^{def}	69.33^{b}	35.53^{cd}	4.59^{bc}	55.27^{c}	7.05^{de}
	50	12.10^{abcde}	7.14^{bcd}	67.03^{c}	34.88^{de}	4.92^{ab}	53.76^{cd}	7.00^{de}
	100	11.44^{def}	7.66^{abc}	66.88^{c}	33.83^{ef}	4.30^{bc}	56.75^{bc}	7.98^{abcd}
D. eriantha	0	11.75^{bcdef}	7.16^{bcd}	59.75^{ef}	35.02^{de}	4.06^{bc}	42.28^{e}	5.61^{f}
	50	11.05^{ef}	8.37^{ab}	59.13^{f}	33.96^{ef}	4.49^{bc}	49.81^{d}	7.46^{cde}
	100	11.63^{cdef}	8.35^{ab}	60.17^{ef}	33.68^{ef}	4.36^{bc}	50.25^{d}	6.68^{ef}
P. maximum	0	12.67^{abcd}	6.77^{cde}	64.84^{d}	36.03^{cd}	3.73^{c}	66.02^{a}	8.31^{abc}
	50	12.97^{abc}	7.60^{abc}	64.64^{d}	36.71^{c}	4.04^{bc}	67.53^{a}	8.66^{ab}
	100	13.37^{a}	8.70^{a}	61.49^{e}	33.36^{f}	4.49^{bc}	70.23^{a}	8.79^{a}
LSD $_{p=0.05}$		1.386	1.380	1.832	1.492	0.975	4.683	1.147
MSE (df)		0.669 (22)	0.664 (22)	1.118 (21)	0.741 (21)	0.332 (22)	6.978 (20)	0.459 (22)

Values within a column with different superscripts differ significantly ($P < 0.05$)
LSD: Least significant difference; MSE: Mean square error; df: degrees of freedom; OM: Organic matter; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; ME: Metabolizable energy

Forage in vitro gas and methane production potential

The *in vitro* total gas (TGP), methane (CH_4) and methanogenic potential (CH_4: total gas production ratio) of the selected species is presented in Table 7.6 and 7.7. There were no differences ($P > 0.05$) found within C4 species as the N fertilization rate increased (Table 7.6) for all *in vitro* parameters at the 24 and the 48-hour incubation periods, except for *C. ciliaris* which showed an increase ($P < 0.05$) in methanogenic potential at the 100 kg N ha^{-1} treatment at the 24 hour incubation interval.

D. eriantha and *C. gayana* had the lowest ($P < 0.05$) TGP and *in vitro* CH_4 production at the control treatment (0 kg N ha^{-1}) after the 24-hour incubation period, respectively for C4 grass species. No differences were found in either TGP or CH_4 production at the 50 kg N ha^{-1} treatment but as the rate of fertilization increased to 100 kg N ha-1 *C. ciliaris* produced the highest *in vitro* methane ($P < 0.05$) at the 24-hour incubation period compared to the other C4 species.

Table 7.5 Effect of nitrogen fertilization on the chemical composition (% of DM) of improved temperate C3 grass species commonly used in South Africa

	N kg/ ha	Ash	CP	NDF	ADF	ADL	IVOMD	ME
D. glomorata	0	15.41^{ab}	8.12^{ef}	58.81^{a}	34.62^{a}	3.90^{abc}	71.70^{b}	10.40^{b}
	50	13.34^{c}	9.69^{d}	58.11^{a}	34.52^{a}	3.46^{bc}	59.66^{c}	10.75^{b}
	100	13.42^{c}	11.75^{b}	54.92^{b}	32.42^{ab}	4.38^{ab}	53.30^{d}	10.49^{b}
F. arundinacea	0	13.76^{bc}	7.41^{f}	53.20^{bcd}	29.17^{c}	4.55^{a}	74.93^{b}	12.60^{ab}
	50	12.84^{c}	9.27^{de}	51.76^{cd}	26.93^{c}	3.48^{bc}	73.34^{b}	12.51^{ab}
	100	12.52^{c}	11.31^{bc}	51.26^{d}	27.73^{c}	3.88^{abc}	75.19^{b}	13.82^{a}
L. perenne	0	15.44^{ab}	7.85^{f}	54.48^{bc}	31.56^{b}	3.35^{c}	81.22^{a}	10.73^{b}
	50	16.50^{a}	10.13^{cd}	54.62^{bc}	33.03^{ab}	3.24^{c}	79.13^{a}	11.71^{ab}
	100	16.00^{a}	13.27^{a}	54.84^{bc}	32.64^{ab}	3.29^{c}	80.15^{a}	11.98^{ab}
LSD $_{p=0.05}$		1.732	1.394	3.118	2.314	0.958	3.787	2.447
MSE (df)		1.002 (16)	0.648 (16)	3.246 (16)	1.788 (16)	0.306 (16)	4.788 (16)	1.999 (16)

Values within a column with different superscripts differ significantly (P < 0.05)
LSD: Least significant difference; MSE: Mean square error; df: degrees of freedom; OM: Organic matter; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; IVOMD: *In vitro* organic matter digestibility; ME: Metabolizable energy

When comparing between the C4 species in the different fertilization treatments after the 48-hour incubation period (Table 7.6), *P. maximum* and *C. ciliaris* had the highest TGP (P < 0.05) and *D. eriantha* the lowest CH_4 (P < 0.05) production at the control (0 kg N ha^{-1}) treatment. No differences were found at the 50 kg N ha^{-1} fertilization rate for *in vitro* CH_4 production between the C4 species with *C. ciliaris* producing the lowest TGP (P < 0.05) compared to the other C4 species after 48 hours of incubation. Similarly, no differences were found in TGP at the 100 kg N ha^{-1} treatment after samples were incubated for 48 hours but *C. gayana* had lower (P < 0.05) in *vitro* CH_4 production compared to *P. maximum*.

Table 7.6 The effect of nitrogen fertilization on the *in vitro* total and methane gas production (ml/ g DM^{-1}) of improved tropical C4 grass species commonly used in South Africa

		24 Hour		48 Hour		CH_4: TG	
	N kg/ ha	TG	CH_4	TG	CH_4	24 hour	48 Hour
C. ciliaris	0	105.28^{abc}	4.68^{ab}	154.59^{abc}	11.00^{ab}	0.044^{b}	0.071^{ab}
	50	98.31^{abcde}	4.35^{bc}	149.05^{abc}	10.96^{ab}	0.045^{b}	0.074^{a}
	100	102.86^{abcd}	5.38^{a}	153.29^{abc}	10.90^{ab}	0.053^{a}	0.070^{abc}
C. gayana	0	85.18^{cde}	3.33^{d}	136.70^{bc}	9.52^{abc}	0.039^{b}	0.069^{abc}
	50	82.20^{de}	3.59^{cd}	135.43^{c}	9.82^{abc}	0.043^{b}	0.072^{ab}
	100	89.20^{bcde}	3.30^{d}	145.84^{abc}	9.06^{bc}	0.037^{b}	0.062^{c}
D. eriantha	0	78.89^{e}	3.50^{cd}	135.73^{c}	8.75^{c}	0.044^{b}	0.064^{bc}
	50	101.79^{abcd}	4.12^{bcd}	160.67^{a}	10.34^{abc}	0.044^{b}	0.064^{bc}
	100	91.19^{abcde}	4.07^{bcd}	151.88^{abc}	10.59^{abc}	0.044^{b}	0.069^{abc}
P. maximum	0	110.44^{a}	4.69^{ab}	162.21^{a}	11.32^{a}	0.043^{b}	0.069^{abc}
	50	106.05^{ab}	4.40^{bc}	157.73^{ab}	11.02^{ab}	0.042^{b}	0.070^{abc}
	100	109.03^{ab}	4.52^{ab}	161.02^{a}	11.18^{a}	0.041^{b}	0.069^{abc}
LSD $_{p=0.05}$		20.676	0.916	21.795	2.053	0.0074	0.0084
MSE (df)		149.096 (22)	0.292 (22)	165.67 (22)	1.469 (22)	<0.0001 (22)	<0.0001 (22)

Values within a column with different superscripts differ significantly (P < 0.05)
LSD: Least significant difference; MSE: Mean square error; df: Degrees of freedom; TG: Total gas.

The *in vitro* total gas, methane, and methanogenic potential for the C3 temperate grass species evaluated are presented in Table 7.7. Increasing the rate of N fertilization increased *in vitro* CH_4 production (P < 0.05) at the 24-hour incubation period for both *D. glomorata* and *F. arundinacea*, and at the 48 hour incubation period for *F. arundinacea*. The level of fertilization had no effect on the methanogenic potential of the selected C3 grass species after 48 hours incubation but increased (P < 0.05) the rate of methane production to TGP at the 24-hour incubation period for *D. glomorata* and *F. arundinacea*. No effects were found on all the *in vitro* gas production parameters for *L. perenne* as the rate of fertilization was increased from 0 to 100 kg N ha^{-1}.

L. perenne consistently had the highest (P < 0.05) methanogenic potential after 48 hours incubation when compared to *D. glomerata* and *F. arundinacea* as the rate of N fertilization increased from 0 to 100 kg N ha^{-1}. Although no differences between the C3 species were found at the 100 kg N ha^{-1} treatment after 24 hours of incubation, *F. arundinacea* and *L. perenne* had the highest and lowest methanogenic potential at the 50 kg N ha^{-1} treatment, respectively.

Table 7.7 The effect of nitrogen fertilization on *in vitro* total and methane gas production (ml/ g DM^{-1}) of improved temperate C3 grass species commonly used in South Africa

		24 Hour		48 Hour		CH4: TG	
	N kg/ ha	TG	CH4	TG	CH4	24 hour	48 Hour
D. glomorata	0	82.29^{e}	3.29^{c}	128.57^{c}	6.95^{d}	0.039^{bc}	0.054^{de}
	50	91.22^{de}	3.86^{bc}	133.86^{c}	6.94^{d}	0.041^{abc}	0.051^{e}
	100	105.67^{cd}	4.87^{b}	147.80^{bc}	8.03^{cd}	0.046^{a}	0.054^{de}
F. arundinacea	0	122.12^{abc}	4.46^{bc}	168.84^{a}	9.46^{bc}	0.036^{c}	0.056^{cde}
	50	133.83^{ab}	6.18^{a}	171.91^{a}	10.05^{ab}	0.046^{a}	0.058^{cd}
	100	139.22^{a}	6.51^{a}	180.18^{a}	11.10^{a}	0.047^{a}	0.062^{bc}
L. perenne	0	114.78^{bc}	4.82^{b}	166.39^{ab}	11.42^{a}	0.042^{ab}	0069^{a}
	50	119.21^{abc}	4.74^{b}	170.69^{a}	11.33^{a}	0.040^{bc}	0.069^{a}
	100	109.59^{cd}	4.55^{bc}	160.90^{ab}	11.11^{a}	0.042^{abc}	0.067^{ab}
LSD $_{p=0.05}$		21.455	1.288	20.993	1.545	0.0061	0.0067
MSE (df)		153.642 (16)	0.554 (16)	147.096 (16)	0.797 (16)	<0.0001 (16)	<0.0001 (16)

Values within a column with different superscripts differ significantly (P < 0.05)
LSD: Least significant difference; MSE: Mean square error; df: Degrees of freedom; TG: Total gas

Discussion

The objective of the study was to elucidate the influence of nitrogen fertilizer application rates on the nutrient concentration, *in vitro* digestibility, *in vitro* total gas and methane production of commonly used improved sub-tropical and temperate grass species in South Africa.

Forage quality

Increasing the rate of N fertilization increased the CP concentration of both tropical and temperate grass species. These results agree with results reported by Morrison *et al.* (1980) and Valk *et al.* (1996). The CP concentration reported in the present trial for both tropical and temperate species are lower than previously reported values for similar species (Pieterse *et al.*, 1997; Johnson *et al.*, 2001; Taute *et al.*, 2002; Navarro-Villa *et al.* 2012; *Bannink et al.* 2013). This might be due to the growth period after fertilization and the regrowth phase harvested in the present study. Wilman (1975) reported that the N content of pastures peak at 10 to 14 days after N fertilization and thereafter decrease over time.

Increasing the rate of N fertilization decreased the NDF and ADF concentration of *C. gayana* and *P. maximum* but it had no effect on the fibre fractions of *C. ciliaris* and *D. eriantha* (Table 7.4).

Similarly, *D. glomorata* showed a decrease in NDF concentration with increasing rate of N fertilization (Table 7.5). The fibre fraction of *F. arundinacea* showed a tendency to decrease with increasing N fertilization but the level of fertilization had no effect on the fibre fractions of *L. perenne*. The inconsistent influence of N fertilization on NDF, ADF and ADL concentrations reported in Table 7.4 and 5 agrees with Minson (1990) and Valk *et al.* (1996) who reported that the physiological stage of development has a greater influence on the fibre fractions of forage compared to the level of N fertilization. A similar inconsistent effect of N fertilization on forage fibre fraction was reported by Peyraud and Astigarra (1998). These authors concluded a specie specific response of forages to N fertilization.

Increasing the rate of N fertilization increased the IVOMD of two of the tropical grass species, *C. ciliaris* and *D. eriantha* but no significant effect was found for *C. gayana* and *P. maximum*. Similarly, Johnson *et al.* (2001) reported an increase in IVOMD for star grass (*Cynodon nlemfuensis*) fertilized with increasing levels of N and Taute *et al.* (2002) reported no effect of N fertilizer on the IVOMD of *P. maximum*. The IVOMD of temperate species was not effected by the rate of N fertilization except for *D. glomorata* which showed a decrease as the rate of N fertilization increased. These results are similar to results reported by Valk *et al.* (1996) and Lovett *et al.* (2004) for *L. perenne*. The decrease in the digestibility of *D. glomorata* can be explained by a slight increase in the lignin concentration with increased N fertilization (Table 7.5). Peyraud and Astigarra (1998) also reported that N fertilization increased the tiller: leave ratio of forages which could have a negative effect on the forage digestibility. Nitrogen fertilization can however have an indirect positive effect on digestibility by enabling an earlier utilization of grass forage. A higher rate of N application allows for grass to be harvested at an earlier physiological age due to an increased growth response and yield (Peyraud and Astigarraga, 1998). This could lead to an increased intake and production from livestock and thus a reduced methane intensity (CH_4 unit product^{-1}) of the pastures.

Gas production

Methane production from forages depend both on the NDF concentration and forage digestibility, which are the two aim drivers of hydrogen production from carbohydrate fermentation in the rumen (Archimede *et al.* 2011). The gas production values reported in Table 7.6 are similar to gas production values reported by Gonzalez Ronquillo *et al.* (1998) for tropical grass species. In the present trial, *C. ciliaris* and *P. maximum* produced the highest average *in vitro* CH_4 values across all fertilization treatments after the 24 and 48-hour incubation periods. This corresponds with a higher NDF concentration and IVOMD (Table 7.4) of these species compared to *D. eriantha* and *C. gayana*. These results correspond with results reported by Gemeda and Hassen (2014) and Doreau *et al.* (2016) who reported a positive correlation between methane production and cell wall contents of forages. *Digitaria eriantha* had the lowest average *in vitro* methane production after the 24 and 48-hour incubation periods and tended to have a lower methanogenic ratio (CH_4: Total gas production) compared to other C4 species (Table 7.6) in the present trial. This could be attributed to the lower IVOMD ($P < 0.05$) of *D. eriantha* (Table 7.4) which might have a negative effect on voluntary intake of the forage and subsequent animal production.

The significant increase in 24 hour CH_4 and methanogenic potential of *D. glomorata* and *F. arundinacea* corresponds with a significant increase in the CP concentration as the rate of N fertilization increased and a reduction in the fibre fraction of the species (Table 7.5). These results differ from data reported by Johnson and Johnson (1995) and Lovett *et al.* (2004) that indicated methane production decreased when feed protein concentration increased. The increase in 24-hour

gas production could have been due to changes in the degradability of the CP and fibre fractions due to an increase in N fertiliser as reported by Valk *et al.* (1996). Crude protein levels above the threshold of 70 g kg DM-1, as reported in the present study, are considered to enhance microbial multiplication in the rumen thus improving fermentation (Njidda and Nasiru, 2010). The negative correlation between NDF concentration and *in vitro* gas production reported by Njidda and Nasiru (2010) and Meale *et al.* (2012) was not realised in the present study. Increasing N fertilization from 0 to 100 kg N ha^{-1} had no effect on the *in vitro* total gas and CH_4 production of *L. perenne* at both the 24 and 48 hour incubation periods. These results differ from results reported by Lovett *et al.* (2004) which showed a significant decrease in the *in vitro* gas and CH_4 production with increasing N application rates to *L. perenne*. These differences may have been due to differences in the physiological age of the forages between the two trials.

In the current study, *D. glomorata* emerged as the C3 species with the lowest methanogenic potential after 48 hours of incubation compared to *F. arundinacea* and *L. perenne*. However, while part of the reduced 48-hour methanogenic potential could be attributed to a reduced methane production it may also be an indication of a reduced overall ruminal fermentation potential. *Dactylis glomorata* had the lowest ($P < 0.05$) TGP after the 48 hour incubation period. This reduce fermentation potential can have negative implications on livestock productivity (*Bannink et al.* 2013).

Conclusion

This study demonstrated significant differences in nutrient composition, digestibility, and *in vitro* gas production characteristics among key South African improved pasture species. Nitrogen fertilization affected the nutrient composition of species but had no effect on the *in vitro* gas production or methane production potential within species. Between species differences were found for 24-hour methane production in sub-tropical and temperate species but these differences diminished at the 48 hour incubation period. The data suggested that the stage of physiological development of forages will have a greater influence on the methanogenic potential of forages compared to the effect of nitrogen fertiliser application. There is a need for further assessment of fermentation characteristics of these species at various stages of maturity.

Acknowledgements

This study forms part of a larger project jointly funded by the Red Meat Research and Development Trust of South Africa and the National Research Foundation of South Africa. The Animal Ethics Committee of the University of Pretoria approved all experimental protocols (ECO18-14) before commencement of the study.

References

Archimede, H., Eugene, M., Marie-Magdeleine, C., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P. and Doreau, M., 2011. Comparison of methane production between C3 and C4 grasses and legumes. Anim. Feed Sci. Technol. 166 – 167, 59 – 64.

AOAC., 2000. Association of Official Analytical Chemists (AOAC). Official method of analysis. 17ed. Association of Official Analytical Chemists, Rockville, MD, USA.

Bannink, B.K., Durmic, Z., Erskine, W., Ghamkhar, K. and Revell, C., 2013. *In vitro* ruminal fermentation characteristics and methane production differ in selected key pasture species in Australia. Crop and Past. Sci. 64, 935 – 942.

Beauchemin, K.A., McAllister, T.A., McGinn, and S.M., 2009. Dietary mitigation of enteric methane from cattle. Perspect. Agric. Vet. Sci. Nutr. Natural Res. 4, 1 – 18.

Benchaar, C., Hassanat, F., Gervais, R., Chouinard, P.Y., Petit, H.V. and Massè, D.I., 2014. Methane production, digestion, ruminal fermentation, nitrogen balance, and milk production of cows fed corn silage- or barley silage-based diets. J. Dairy Sci. 97, 961 – 974.

Doreau, M., Benhissi, H., Thior, Y.E., Bois, B., Genestoux, L., Lecomte, P., Morgavi, D.P. and Ickowicz, A., 2016. Methanogenic potential of forages consumed throughout the year by cattle in a Sahelian pastoral area. Anim. Prod. Sci. 56, 613 – 618.

Du Toit, C.J.L., Meissner, H.H. and Van Niekerk, W.A., 2013a. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43 (3), 320 – 339.

Du Toit, C.J.L., Meissner, H.H. and Van Niekerk, W.A., 2013c. Direct greenhouse gas emissions of the game industry in South Africa. S. Afr. J. Anim. Sci. 43 (3), 376 – 393.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013b. Direct greenhouse gas emissions of the South African small stock sectors. S. Afr. J. Anim. Sci. 43 (3), 340 – 361.

Durmic, Z., Hutton, P., Emms, J., Hughes, S. and Verce, P., 2010. *In vitro* fermentation traits of Australian woody perennial plant species that may be considered as potential sources of feed for grazing ruminants. Anim. Feed Sci. Technol. 160, 98 – 109.

Engels, E.A.N. and Van der Merwe, F.J. 1967., Application of an *in vitro* technique to South African forages with special reference to affect certain factors on the results. S. Afr. J. Agric. Sci. 10, 983 – 995.

Gemeda, B.S. and Hassen, A., 2014. *In vitro* fermentation, digestibility, and methane production of tropical perennial grass species. Crop and Past. Sci. 65, 479 – 488.

Glass, G.V., Peckham, P.D. and Sanders, J.R., 1972. Consequences of Failure to meet assumptions underlying the fixed effects analyses of variance and covariance. Rev. Ed. Res. 42 (3), 237-288.

Goel, G. and Makkar, H.P.S., 2012. Methane mitigation from ruminants using tannins and saponins, a status review. Trop. Anim. Health Prod. 44, 729 – 729.

Goering, H.K. and Van Soest, P.J., 1988. Forage fiber analysis, apparatus, reagents, procedures, and some applications. USDA-ARS, Washington, DC, USA. (Agriculture Handbok, 379).

Gonzalez Ronquillo, M., Fondevila, M., Barrios Urdaneta, A. and Newman, Y., 1998. *In vitro* gas production from buffel grass (*Cenchrus ciliaris* L.) fermentation in relation to the cutting level, the level of nitrogen fertilization and the season of growth. Anim. Feed Sci. Technol. 72, 19 – 32.

Johnson, C.R., Reiling, B.A., Mislevy, P. and Hall, M.B., 2001. Effects of nitrogen fertilization and harvest date on yield, digestibility, fibre and protein fraction of tropical grasses. J. Anim. Sci. 79, 2439 – 2448.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483 –

2492.

Lovett, D., McGilloway, D., Bortolozzo, A., Hawkins, M., Callan, J., Flynn, B. and O'Mara, F., 2006. *In vitro* fermentation patterns and methane production as influenced by cultivar and season of harvest of *Lolium perenne* L. Grass and Forage Sci. 61, 9 – 21.

Lovett, D.K., Bortolozzo, A., Conaghan, P., O'Kiely, P. and O'Mara, F.P., 2004. *In vitro* total and methane gas production as influenced by rate of nitrogen application, season of harvest and perennial ryegrass cultivar. Grass and Forage Sci. 59, 227 – 232.

Meale, S.J., Chaves, A.V., Baah, J. and McAllister, T.A., 2012. Methane production of different forages in *in vitro* ruminal fermentation. Asian-Aust. J. Anim. Sci. 25 (1), 86 – 91.

Meissner, H.H., Scholtz, M.M. and Engelbrecht, F.C., 2013. Sustainability of the South African livestock sector towards 2050. Part 2: Challenges, changes and required implementations. S. Afr. J. Anim. Sci. 43 (3), 298 – 319.

Minson, D.J., 1979. Relationships of conventional and preferred fractions to determine energy values. Proc. Workshop on analytical methods. Ottawa, Canada.

Minson, D.J., 1990. Forage in ruminant nutrition. Academic Press, San Diego, CA: 483.

Morison, J., Jackson, M.V. and Sparrow, P.E., 1980. The response of perennial ryegrass to fertilizer nitrogen in relation to climate and soil. Grassland Research Institute, Hurley, Technical report No 27, 71

Mould, F.L., Morgan, R., Kliem, K.E. and Krystallidou, E., 2005. A review and simplification of the *in vitro* incubation medium. Anim. Feed Sci. Technol. 123 – 124, 155 – 172.

Navarro-Villa, A., O'Brien, M., Lopez, S., Boland, T.M. and O'Kiely, P., 2012. *In vitro* rumen methane output of grasses and grass silages differing in fermentation characteristics using the gas-production technique (GPT). Grass and Forage Sci. 67 (4), 472 – 487.

Njidda, A.A and Nasiru, A., 2010. *In vitro* gas production and dry matter digestibility of tannin containing forages of a semi-arid region of north-eastern Nigeria. Pak. J. Nutr. 9, 60 – 66.

Peyraud, J.L. and Astigarraga, L., 1998. Review of the effect of nitrogen fertilization on the chemical composition, intake, digestion, and nutritive value of fresh herbage: consequences on animal nutrition and N balance. Anim. Feed Sci. Technol. 72, 235 – 259.

Pieterse, P.A., Rethman, N.F.G. and Van Bosch, J., 1997. Production, water use efficiency and quality of four cultivars of Panicum maximum a different levels of nitrogen fertilization. Trop. Grasslands 31, 117 – 123.

Robinson, P.H., Givens, D.I. and Getachew, G., 2004. Evaluation of NRC, UC Davis and ADAS approaches to estimate the meatobolizable energy values of feeds at maintenance energy intake from equations utilizing chemical essays and *in vitro* determinations. Anim. Feed Sci. Technol. 114 (1 – 4), 75 – 90.

SAS Institute, Inc., 1999. SAS/STAT User's Guide, Version 9, 1st printing, Volume 2. SAS Institute Inc, SAS Campus Drive, Cary, North Carolina 27513.

Shapiro, S. S. and Wilk, M. B., 1965. An Analysis of Variance Test for Normality (complete samples). Biometrika, 52, 591-611.

Taute, A., Van Niekerk, W.A., Rethman, N.F.G. and Coertze, R.J., 2002. An evaluation on

nitrogen fertilised Panicum maximum cv. Gatton at different stages of maturity during autumn: 1. Dry matter yield and certain qualitative parameters. S. Afr. J. Anim. Sci. 32 (3), 208 – 216.

Theodorou, M.K., Williams, B.A., Dhanoa, M.S., McAllen, A.B. and France, J., 1994. A simple gas production method using pressure transducers to determine the fermentation kinetics of ruminant feed. Anim. Feed Sci. Technol. 48, 185 – 197.

Tilley, J.M.A. and Terry, R.A., 1963. A two-stage technique for the *in vitro* digestion of forage crops. J. Brit. Grasslands Soc. 18, 104 – 111.

Valk, H., Kappers, I.E. and Tamminga, S., 1996. *In sacco* degradation characteristics of organic matter, neutral detergent fibre and crude protein of fresh grass fertilised with different amounts of nitrogen. Anim. Feed Sci. Technol. 63, 63 – 87.

Van Soest P.J., Robertson, P.J. and Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583 – 3597.

Wilman, D., 1975. Nitrogen and Italian ryegrass: 2. Growth up to 14 weeks: nitrogen, phosphorus and potassium content and yield. J. Brit. Grassland Soc. 31, 243 – 247.

Chapter 8

Methane emissions from sheep fed *Eragrostis curvula* hay substituted with *Lespedeza cuneata*

C.J.L du Toit[1,2#], W.A. van Niekerk[2], H.H. Meissner[3], L.J. Erasmus[2] and R.J. Coertze[2]

[1]Department of Animal Science, Tshwane University of Technology, Private Bag X680, Pretoria, 0001, South Africa

[2]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[3]No 3 Die Hoewes, 276 von Willich Street, Centurion, 0157, South Africa
[#]Corresponding author: dutoitcjl@tut.ac.za; Tel: +27123824292; Fax: +27123825220

Abstract

The objective of this study was to investigate the effect of feeding condensed tannin-containing *Lespedeza cuneata* hay at different levels on the feed intake and methane (CH_4) emissions of sheep fed a basal diet of sub-tropical *Eragrostis curvula* hay. Four adult ruminally cannulated Dohne-Merino wethers with an initial body weight of 65.5 ± 3.5 kg were used in a 4 x 4 Latin square design. The experimental treatments were T1: 100% *E. curvula*: 0% *L. cuneata*; T2: 70% *E. curvula*: 30% *L. cuneata*; T3: 40% *E. curvula*: 60% *L. cuneata*; T4: 10% *E. curvula*: 90% *L. cuneata*. Each of the four experimental periods lasted for 27 days consisting of a 14 day adaptation period, a 7 day digestibility trial, and a 6 day methane measurement period. During the 6 day methane measurement period methane emissions were measured continuously over a 24 hour period using an open circuit respiration system. The dry matter intake (g/kg $W^{0.75}$) was higher ($P<0.05$) for sheep receiving T3 and T4 compared to T1 and T2 (77.33 and 84.67 g/kg $W^{0.75}$ compared to 62.96 and 62.71 g/kg $W^{0.75}$, respectively). The increase in DMI corresponded with a linear increase in the dry matter digestibility of the experimental treatments from 38% DM to 45% of DM as the level of *L. cuneata* substitution increased from T1 to T4. Methane emissions (g/ kg DMI) was not influenced ($P>0.05$) by the 30% inclusion level of *L. cuneata* but decreased ($P<0.05$) as the level increased to 60% and 90% from 17.6 g CH_4/kg DMI to 13.8 g CH_4/kg DMI and 14.3 g CH_4/kg DMI respectively. The results suggest that *L. cuneata* has the potential to reduce CH_4 emissions and possibly increase production from sheep by improving the dry matter digestibility and through improved dry matter intake.

Key words: sericea lespedza, rumen fermentation, respiration chamber, methane mitigation

Introduction

Reducing emissions of greenhouse gases (GHG) from livestock production systems is a global research priority. The effects of climate change are predicted to be highly dynamic and it can have adverse effects on crop and livestock production, particularly in developing countries (Scholtz *et al*., 2011). Numerous CH_4 mitigation strategies and technologies have been explored over the past decade, including interventions in livestock management, dietary composition, ruminal fermentation and altering the methanogen population in the rumen (Patra *et al*., 2017). Recent reviews on the mitigation of methane emission form livestock have showed that the viable options for mitigation have diminished over the past decade with many options showing inconsistent efficacy or impracticality for inclusion into livestock production systems (Hart *et al*., 2008; Patra

et al., 2017). Most of the methane (CH_4) mitigation strategies has focussed on intensively managed ruminants fed high quality diets based on total mixed rations and animals grazing temperate pastures (Hristov *et al*., 2013). In contrast, the number of publications on mitigation strategies for sheep grazing low quality sub-tropical pastures is limited.

Ruminal micro-organisms digest plant fibre fractions into forms usable by livestock. During the process of ruminal fermentation enteric CH_4 is produced by methanogenic micro-organisms from the disposal of metabolic hydrogen (H_2) not utilized during the formation of volatile fatty acids (VFA) (Newbold *et al*., 2005). This process represents a loss of gross energy (GE) to livestock (Patra and Saxena, 2010). Several researchers have reported reduced CH_4 emissions from ruminants consuming forages containing condensed tannins (CT), determined *in vitro* and *in vivo* from cattle and goats (Woodward *et al*., 2002; Min *et al*., 2003; Animut *et al*., 2008). Puchala *et al*. (2005) reported that the effect of CT in ruminants varies with the type of tannin or plant source and that ruminant species vary in their response to consuming CT containing forages. Tannins are compounds of high molecular weight containing reactive phenolic hydroxyl or carboxyl groups that enables it to complex with protein, minerals, and other macromolecules (Reed, 1995). Jones and Mangan (1977) reported that tannin-protein complexes are pH dependent and stable between pH 3.7 and 7.0 but dissociates below a pH 3.5 (Sinclair *et al*., 2009). Forage sources containing tannins have lower ruminal degradability and might, in addition to reducing CH_4, offer the potential of increasing the flow of undegradable protein to the small intestine, improving animal performance (Sinclair *et al*., 2009).

Lespedeza cuneata has been identified as a perennial legume high in condensed tannins (Puchala *et al*., 2012) and it is well adapted to low pH marginal agricultural soils in South Africa (Wasserman, 1981). The objective of this study was to investigate the effect of substituting an *E. curvula* hay diet with different levels of *L. cuneata* containing CT, on dry matter intake, digestibility, and enteric methane emissions by sheep.

Material and Methods

The study was conducted at the Hatfield experimental farm of the University of Pretoria, South Africa. The Animal Ethics Committee of the University of Pretoria approved all experimental protocols (ECO18-14) before commencement of the study.

Animals and treatments

Four adult ruminally cannulated Dohne-Merino wethers with an initial body weight (BW) of 65.5 ± 3.5 kg were used in a 4 x 4 Latin square design. All animals were accustomed to experimental procedures and treated for internal and external parasites and each received an injectable vitamin A, D, and E supplement prior to the start of the study. The experimental treatments entailed the feeding of commercially sourced *E. curvula* hay substituted with 0%, 30%, 60% and 90% *L. cuneata* hay on a dry matter basis as treatments 1 to 4, respectively. The *L. cuneata* hay contained 17.7 mg CT/ g DM. All diets were offered as hammer milled hay to a particle length of 2 to 3 cm to ensure thorough mixing and prevent separation of particles when fed. The trial ran across four experimental periods. Each period lasted for 27 days consisting of a 14 day adaptation period, a 7 day digestibility trial, and a 6 day methane measurement period. After each experimental period sheep were penned as a group and fed a 50:50 high quality forage/ legume diet (consisting of E. curvula and M. sativa hay) for two weeks prior to the start of the next experimental period to improve nutritional status and minimise possible carryover effect of experimental diets.

Digestibility trial

At the start of each experimental period the sheep were weighed and housed in individual metabolic crates for the duration of the digestibility study. They were offered the experimental diets *ad libitum* at 08h00 and 15h30 daily and had free access to water and a commercial mineral supplement. After the adaptation period they were fitted with faecal collection bags and total daily feed intake and faecal output were recorded according to Kennedy and Charmley (2012). Subsamples of feed offered were collected daily and dried at 55°C for 48 hours. These subsamples were pooled at the end of the collection period and stored for analysis. Total daily feed refusals and faecal output were collected daily before the morning feeding, weighed and subsamples of feed refusals and faeces were taken. Feed refusals were dried at 55°C for 48 hours and stored. Feed refusals were analysed to determine the nutrient intake of animals on specific experimental diets according to Osuji *et al*. (1993). Faecal material was sampled and stored at -20°C. At the end of the collection period representative samples were taken and dried at 55°C in a forced air oven for analysis.

After the digestibility collection period 12 representative rumen fluid samples were taken from various parts of the rumen through the rumen cannula over a 72-hour period at 08h00, 12h00, 16h00, 20h00, 00h00, 04h00, 10h00, 14h00, 18h00, 22h00, 02h00, 06h00. Rumen samples were filtered through 4-layers of cheesecloth and the remaining material returned to the rumen. The pH of the rumen fluid samples was taken prior to being preserved with 4ml of a 25% H_3PO_4 solution per 20ml of rumen fluid for volatile fatty acid (VFA) determination, as described by Webb (1994) and 5ml of a 50% H_2SO_4 solution per 30ml of rumen fluid for NH_3–N determination, as described by Broderick and Kang (1980). All rumen fluid samples were stored at -20°C before analysis of ruminal NH_3-N and ruminal VFA.

Methane measurement

After completion of the digestibility study the sheep were moved to open circuit respiration chambers for 6 days. Methane was measured using four chambers arranged in two rows of two with a 2m corridor between the two rows. The sheep were allowed to acclimatize for the first 3 days in the chambers, thereafter CH_4 was recorded over a 24 hour period. The chamber construction and operation was based on respiration chambers at Aberystwyth University (Hart *et al*., 2012) as described by Gemeda (2014). Methane concentration was measured per second continuously over a 5 min period per chamber using an multigas analyser with a solid state non dispersive infrared aborption detector (ADC MGA3000, Spurling works, Herts, UK). It took 20 min to sequentially sample the airflow in all chambers where after the system was calibrated using a zero gas (100% nitrogen gas) and a span gas (150ppm CH_4 standard gas). All animals received the experimental diets twice daily at 08h00 and 15h30 *ad libitum* and had free access to water and a commercial mineral supplement. Daily feed intake was determined as described above. Chamber floors were cleaned during the morning feed in between the measuring periods of each chamber to minimize interruptions. The methane flux for each chamber was calculated as the average flux over each of the 48 sampling times in the 24 hour sampling period. Gas recovery tests were conducted on individual chambers at the start of each sampling period, according to the method described by Hart *et al*. (2012). The average recovery rate was 98.7%, 100%, 97.9% and 101.9% for the four chambers used respectively. All chamber data was corrected for gas recovery rates.

Sample analysis

Samples of experimental diets, feed refusals, and faeces were ground to pass a 1mm screen after drying in a forced air oven at 55°C for 48 hours. Samples were analysed for dry matter (DM), ash, nitrogen (N), ether extract (EE), calcium (Ca) and phosphorous (P) according to procedures of the AOAC (2000). Samples were also analysed for neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentration using an ANKOM 200/220 Fibre Analyser (ANKOM Technology, Fairport, NY, USA) based on the methods described by Van Soest *et al*. (1991). Sodium sulphite and heat stable amylase were used in the analysis of NDF. The NDF and ADF were expressed inclusive of residual ash. The lignin concentration (ADL) was determined according to Van Soest *et al*. (1991) through the solubilisation cellulose with sulfuric acid in the ADF residue. Acid detergent insoluble nitrogen (ADIN) was determined from the ADF analysis followed by N analysis. Samples were analysed for gross energy (GE) using a bomb calorimeter (Parr 3600, Parr Instrument Co. Inc., Moline, IL, USA) according to the AOAC (2000). Samples of the *E. curvula* and *L. cuneata* hay were mixed with diatomaceous earth and extracted with 70% methanol in steel extraction cells of an accelerated solvent extraction system (ASE 200, Dionex, Sunnyvale, CA) for tannin concentration analysis. Tannins were analysed by means of the vanillin-HCL method of Broadhurst and Jones (1978). The metabolizable energy (ME) concentrations of the experimental treatments were estimated according to AFRC (1993) from diet digestible organic matter (DOM). Sample non-fibre carbohydrates (NFC) were estimated according to Fox *et al*. (2004). Rumen fluid samples were analysed for ammonia-N and volatile fatty acids (VFA) according to procedures described by Broderick and Kang (1980) and Webb (1994).

Statistical analysis

An analysis of variance using the GLM model of SAS (SAS, 2015) for a Latin square design was used for all the variables to determine differences between periods, treatments, and sheep. The means and the standard error of the means (SEM) were calculated, while the significance of differences ($P < 0.05$) and tendencies ($P \leq 0.10$) between means were determined using Fischer's test (Samuels and Wittmer, 2003).

Results

Roughage composition

The chemical composition (DM basis) of the experimental diets offered is presented in Table 8.1. Substituting *E. curvula* hay with *L. cuneata* hay increased ($P<0.05$) the CP concentration of the diets from 9.3% to 13.3% from the control (T 1) to the 90% substitution level (T 4). Neutral detergent fibre and ADF concentrations decreased ($P<0.05$) with increased levels of *L. cuneata* substitution. The lignin (ADL) concentration of diets increased with increased levels of *L. cuneata* in experimental diets ranging from 8.32% to 14.4% from the control (T 1) to the 90% substitution level (T 4). The EE concentration of diets was not affected by experimental treatments but the NFC increased ($P<0.05$) from 4.07% to 30.3% from pure *E. curvula* hay to the 90% *L. cuneata* substituted diet (T 4).

Table 8.1 Nutrient composition of experimental diets fed to sheep (% of DM)

	Experimental treatment				
Item (% of DM)	**T1**	**T2**	**T3**	**T4**	**SEM**
OM	94.9	94.8	94.7	94.2	0.21
CP	9.3^{c}	11.7^{b}	13.2^{a}	13.3^{a}	0.27
NDF	79.9^{a}	68.0^{b}	58.4^{c}	49.08^{d}	1.10
ADF	45.9^{a}	45.1^{a}	44.3^{a}	41.8^{b}	0.50
ADL	8.3^{d}	11.5^{c}	12.6^{b}	14.4^{a}	0.26
ADIN	2.4^{c}	3.3^{b}	3.6^{b}	4.9^{a}	0.12
EE	1.5	1.6	1.6	1.6	0.47
NFC	4.1^{d}	13.5^{c}	21.5^{b}	30.3^{a}	0.01
GE MJ/ kg DM	16.9	18.0	17.2	17.4	0.01
ME MJ/ kg DM	5.9	6.4	6.6	5.8	0.32
Ca	0.3^{d}	0.4^{c}	0.6^{b}	0.7^{a}	1.04
P	0.2	0.2	0.2	0.2	0.31
CT mg/ g DM	0^{d}	0.5^{c}	1.1^{b}	1.5^{a}	0.01

T1: 100% *E. curvula*: 0% *L. cuneata*; T2: 70% *E. curvula*: 30% *L. cuneata*; T3: 40% *E. curvula*: 60% *L. cuneata*; T4: 10% *E. curvula*: 90% *L. cuneata*; OM: Organic matter; CP: Crude protein; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: Acid detergent lignin; ADIN: Acid detergent insoluble nitrogen; EE: Ether extract; NFC: Non-fibre carbohydrate; GE: Gross energy; Ca: Calcium; P: Phosphorous; ME: Metabolizable energy; CT: Condensed tannins.

^{a,b,c,d} Means with different superscripts in the same row differ (P<0.05)

SEM: Standard error of means

There were no differences in GE and ME concentrations across the experimental treatments. The P concentrations were not affected by experimental treatments but Ca concentrations increased (P<0.05) with increased levels of *L. cuneata* substitution. The *L. cuneata* hay utilized in the study contained a CT concentration of 17.7 mg/ g DM. Increasing the *L. cuneata* content of the experimental diets increased the CT (P<0.05) concentration from 0 for T 1 to respectively 0.53, 1.06, and 1.53mg/g DM for Treatments 2, 3, and 4.

Body weight, intake, digestion, and methane production

The results in Table 8.2 show that the average live weights of the sheep were 65.4, 66, 65.3 and 64 kg for Treatments 1, 2, 3 and 4 respectively. Dry matter intake (DMI), diet digestibility and methane (CH_4) production are also reported in Table 8.2. Substituting *E. curvula* hay with *L. cuneata* hay increased the apparent diet dry matter digestibility (aDMD) from 38% (T 1) to 45% of DM at the 90% substitution level (T 4). Daily dry matter intake (DMI) was similar for T 1 and T 2 but increased (P<0.05) in sheep receiving T 3 and T 4. The gross energy intake (GEI), digestible dry matter intake (DDMI) and digestible organic matter intake (DOMI) all showed a similar pattern to the DMI across all experimental treatments. Daily CH_4 emissions (g/day) were not affected by the experimental treatments, but CH_4 emissions per kg DMI decreased (P<0.05) with increased levels of *L. cuneata* substitution. Methane emissions expressed as g CH_4/ g mDDMI.$W^{-0.75}$ decreased (P<0.05) as the level of substitution was increased from 30% (T2) to 60% (T3) and from 30% (T2) to 90% (T4). The energy expenditure as CH_4 (MJ/day) was unaffected by the treatments but the ratio of CH_4 energy as a percentage of gross GEI decreased (P<0.05) from T 1 to T 3 and from T 1 to T 4.

Table 8.2 Body weight, dry matter intake, diet digestibility and methane emissions of sheep consuming *Eragrostis curvula* hay substituted with *Lezpedeza cuneata* hay

	Experimental treatments				SEM
Item	**T1**	**T2**	**T3**	**T4**	
LW(kg)	65.4	66	65.3	64	1.94
aDMD (%)	38^{b}	41^{ab}	42^{ab}	45^{a}	2.01
Intake					
DMI (kg/d)	1.4^{b}	1.3^{b}	1.6^{a}	1.8^{a}	0.07
DMI (g/kg $W^{0.75}$)	63.0^{b}	62.71	77.3^{a}	84.7^{a}	2.65
GEI (MJ/ d)	23.1^{b}	23.0^{b}	28.3^{a}	31.2^{a}	1.23
DDMI (g/kg $W^{0.75}$)	24.2^{b}	25.1^{b}	32.8^{a}	38.2^{a}	2.16
DOMI (g/kg $W^{0.75}$)	17.1^{c}	20.8^{bc}	28.0^{ab}	32.0^{a}	2.55
Methane emissions					
CH_4 (g/d)	24.1	22.5	22.5	25.7	1.40
CH_4 (g/ kg DMI)	17.6^{a}	16.8^{ac}	13.8^{b}	14.3^{bc}	0.80
CH_4 (g/g mDDMI)	1.1^{a}	0.9^{a}	0.7^{b}	0.7^{b}	0.06
CH_4 (g/g mDOMI)	1.7^{a}	1.1^{ac}	0.8^{bc}	0.8^{bc}	0.25
CH_4 (% GEI)	6.3^{a}	5.9^{ac}	4.8^{bc}	4.9^{bc}	0.30

T1: 100% *E. curvula*: 0% *L. cuneata*; T2: 70% *E. curvula*: 30% *L. cuneata*; T3: 40% *E. curvula*: 60% *L. cuneata*; T4: 10% *E. curvula*: 90% *L. cuneata*; LW: Live weight; DMI: Dry matter intake; aDMD: Apparent dry matter digestibility; DDMI: Digestible dry matter intake; DOMI: Digestible organic matter intake; GEI: Gross energy intake; CH_4: Methane; mDDMI: Digestible dry matter intake per kg $W^{0.75}$; mDOMI: Digestible organic matter intake per kg $W^{0.75}$
^{a,b,c,d} Means with different superscripts in the same row differ (P<0.05)
SEM: Standard error of means

Ruminal fermentation

The results for rumen pH, rumen ammonia-N (NH_3-N) and volatile fatty acid (VFA) production are presented in Table 8.3. There were no differences (P>0.05) in ruminal pH and rumen ammonia-N across the experimental treatments (Table 8.3). The total VFA concentrations did not differ between the experimental treatments, except at T 3 which resulted in a lower (P<0.05) total VFA production compared to T 1 and T 4. Differences (P<0.05) were observed for the individual VFA ratios (Table 8.3). Acetate as a molar proportion of the total VFA concentration decreased (P<0.05) with increased levels of *L. cuneata* substitution ranging from 71.4% in T 1 to 59.7% in T 4. No differences were found in propionate proportion between T 1 and T 2 but an increase (P<0.05) in propionate proportion resulted from T 1 to T 3 and from T 1 to T 4 (22.3% to 25.1% and 22.3% to 24.3%), respectively. The molar proportion of butyrate increased across all treatments from 6.35% (T 1) to 16% (T 4) whereas a decrease in the acetate: propionate ratio (A: P) resulted when the level of *L. cuneata* substitution was increased from 30% (T2) to 60% (T3) and from 30% (T2) to 90% (T4).

Table 8.3 Rumen pH, ammonia-nitrogen and volatile fatty acid concentration in sheep fed *Eragrostis curvula* hay substituted with *Lespedeza cuneata* hay

	Experimental treatments				
Item	**T1**	**T2**	**T3**	**T4**	**SEM**
Ruminal pH	6.4	6.5	6.5	6.5	0.08
NH3-N (mg/ 100ml)	5.2	4.8	4.5	3.9	0.55
Total VFA (mmol/L)	49.9^{a}	48.9^{ac}	46.8^{bc}	49.6^{a}	0.56
Acetate (%)	71.4^{a}	65.8^{b}	61.6^{c}	59.7^{d}	0.52
Propionate (%)	22.3^{b}	22.5^{bc}	25.1^{a}	24.3^{ac}	0.46
Butyrate (%)	6.4^{d}	11.7^{c}	13.3^{b}	16.0^{a}	0.33
A:P ratio	3.9^{a}	3.0^{a}	2.5^{b}	2.5^{b}	0.11

T1: 100% *E. curvula*: 0% *L. cuneata*; T2: 70% *E. curvula*: 30% *L. cuneata*; T3: 40% *E. curvula*: 60% *L. cuneata*; T4: 10% *E. curvula*: 90% *L. cuneata*; NH3-N: Rumen ammonia-N; VFA: Volatile fatty acid; A:P acetate: propionate ratio.
^{a,b,c,d} Means with different superscripts in the same row differ (P<0.05)
SEM: Standard error of means

Discussion

Roughage composition

The increase (P<0.05) in CP, ADIN, ADL, NFC, Ca and the decrease in diet NDF concentration (P<0.05) as the level of *L. cuneata* increased in the experimental diets reflects the higher quality of the *L. cuneata* substitution diets compared to the pure *E. curvula* basal diet (T1). The CT concentration in *L. cuneata* in the current study (17.7 g/kg DM) was lower than CT concentrations reported for *Lespedeza* spp. in previous studies (Terrill *et al*., 1989; Puchala *et al*., 2005; Animut *et al*., 2008; Puchala *et al*., 2012) ranging from 34g/kg DM to 199 g/kg DM. These differences could be due to climatologically variations during the growth period of the forage, cultivar variations and Terrill *et al*. (1989) reported that the drying method employed to preserve *L. cuneata* affected the CT concentration of the forage with a decrease in CT concentration when *L. cuneata* was dried as a hay. The CP concentration of all the experimental diets was above the minimum level of between 7 and 8% required for optimal microbial function in the rumen (Norton, 2003).

Dry matter intake, digestion, and methane production

The DMI reported in Table 8.2 is similar and higher than values reported by Reid *et al*. (1990) for sheep receiving C4 grass diets of 65.8 g/kg $W^{0.75}$ and by Animut *et al*. (2008) for goats receiving *L. cuneata* diets of 66.1 g/kg $W^{0.75}$ respectively. In the present study DMI increased with higher levels of *L. cuneata* substitution in the diets from T 1 and T 2 to T 3 and T 4 (P<0.05). Treatments 3 and 4 had higher CP concentrations (P<0.05), and lower NDF concentrations (P<0.05) compared to T 1 and T 2 (Table 8.1). McDonald *et al*. (2011) stated that voluntary feed intake is closely related to the rate of digestion of feed and that the NDF concentration of feedstuffs played a major role in the rate of digestion of forages. This is supported by the aDMD of the experimental treatments reported in Table 8.2 of 38%, 41%, 42% and 45% for Treatments 1, 2, 3, and 4 respectively. Aitchison *et al*. (1986) also reported that DM and NDF digestion are higher for legumes compared to grasses. The aDMD reported in Table 8.2 is lower than expected for T 3 and

T 4 with NDF concentrations of 58.4% and, 49.0% and NFC concentrations of 21.5% and 30.3%, respectively. This could partially be explained by the lignin and the tannin concentrations that increased (P<0.05) with increasing levels of *L. cuneata* in the experimental diets ranging from 8.32% to 14.4% and 0% to 1.53% for lignin and tannin respectively. The ratio of NDF to ADF concentration in the present study became smaller as the level of *L. cuneata* in the diets increased. Puchala *et al*. (2005) reported similar results for *L. cuneata* and these authors related the results to the presence of CT in *L. cuneata*. It was not clear if the presence of CT affected the DMI in the present study probably due to the relative low concentrations of CT in the experimental diets. Bhatta *et al*. (2002) reported that CT in forages negatively affected DMI when present in concentrations greater than of 6% of DM. The extent to which lignin in the diets containing *L. cuneata* influenced the digestibility is also unclear as the lignin in legumes influences the digestibility of other cell wall constituents less adversely than lignin in grasses (Puchala *et al*., 2005) possibly due to differences in the differential partitioning of lignin among plant tissues between legumes and tropical grasses (Moore and Jung, 2001). The DDMI and DOMI reported in Table 8.2 is higher than values reported by Animut *et al*. (2008) for diets containing *L. cuneata*. This might have been due to a lower CT concentration of *L. cuneata* in the present study.

Daily CH_4 emissions were similar (P>0.05) across all experimental diets (Table 8.2) ranging from 22.5 g/day to 25.7 g/day. These values are similar to values reported by Pelchen and Peters (1998) in a review of sheep CH_4 emissions ranging from 20.5 g/d to 23.2 g/d across a variety of diets. Animut *et al*. (2008) and Hammond *et al*. (2013) reported higher daily CH_4 emission from sheep fed a diet of 100% *L. cuneata* (33.3 g/d) and sheep receiving a fresh ryegrass/ white clover diet (24.0 to 31.8 g/d) respectively. The daily CH_4 emissions in the present study are comparable to predicted daily CH_4 values for South African sheep in commercial operations ranging from 22.6g/d to 29.0 g/d (Du Toit *et al*., 2013).

The CH_4 emissions expressed as g/kg DMI decreased (P<0.05) from T 1 to T 3 and from T 1 to T 4 with the lowest CH_4 emissions found for T 3 (60% *L. cuneata*) of 13.8 g/kg DMI. The higher CH_4 production (g/kg DMI) reported in Table 8.2 for Treatments 1 and 2 could be due to the associated higher concentrations of cell wall components (NDF and ADF) and lower concentrations of CP and NFC compared to T 3 and T 4. Gemeda and Hassen (2015) reported a negative correlation between *in vitro* CH_4 production and the NFC, CP and ADIN concentrations in feed samples. These authors also reported a positive correlation between forage fibre concentration and *in vitro* CH_4 production. Similarly, Eun *et al*. (2004) reported a positive relationship between CH_4 production and the fibre concentration in livestock diets. Although not measured in the current study, the increased intake of sheep fed T 3 and T 4 suggests an increased rate of passage of feed particles in the rumen. An increased rate of passage is associated with a reduction in ruminal CH_4 production in sheep (Reid *et al*.,1990; Muetzel and Clark, 2015).

Carulla *et al*. (2005) reported CH_4 emissions of 4.9 to 5.3% of GEI by growing wethers with *ad libitum* consumption of ryegrass fed alone or mixed with red clover or lucerne. Similarly, Ominski *et al*. (2006) and Chaves *et al*. (2006) reported CH_4 emissions from cattle receiving diets ranging from 46 to 61% NDF of 5.1 to 5.9% and 4.6 to 6.6% of GEI, respectively. Methane emissions relative to GEI in the present study were similar to these values reported in the literature and decreased (P<0.05) as the level of *L. cuneata* substitution in the experimental treatments increased. This decrease in CH_4 (% GEI) could be explained by the higher digestibility and higher DMI of sheep fed diets containing 60% (T3) and 90% (T4) *L. cuneata* in the present study (Johnson and Johnson, 1995; Benchaar *et al*. 2001). Tannins decrease CH_4 production by directly inhibiting

methanogens and indirectly decreasing H_2 production as a result of decreased fibre digestion and protozoal population in the rumen (Patra et. al. 2017). Previous researchers have shown that supplementing diets with CT (from various sources) decreased *in vitro* and *in vivo* CH_4 production (Tan *et al*., 2011; Hassanat and Benchaar, 2013; Yang *et al*., 2016). These earlier results indicated that either CT or hydrolysable tannins (HT) at certain levels inhibit rumen CH_4 production, but that the extent of the reduction depends on the tannin source and possibly the composition of the diet (Yang *et al*., 2016). Methane production (g/kg $W^{0.75}$ and as % GEI) in the present study decreased as the concentration of the CT in the experimental diets increased. Although the data suggest a mitigation effect of CT in the present study the authors were unable to confirm the effect of tannins as the experimental treatments were not replicated with the inclusion of polyethylene glycol (PEG) to inhibit the effect of CT on dietary parameters, DMI and digestibility in the present study.

Rumen pH and fermentation

Diet composition can influence rumen fermentation and ruminal CH_4 production as a result of altered VFA production or a reduced degradation of feed consumed in the rumen (Bell *et al*., 2016). Both ruminal pH and ruminal ammonia nitrogen (NH_3-N) was not affected ($P>0.05$) by the experimental treatments (Table 8.3) in the present study. Although a numerical decrease in ruminal NH_3-N was observed in Table 8.3, the increase ($P<0.05$) in diet CP concentration and DMI reported in Table 8.1 and Table 8.2 did not affect the rumen NH_3-N concentration in sheep fed diets containing *L. cuneata*. Kanjanapruthipong and Leng (1998) stated that the effective degradability of tropical roughages fed to sheep was maximised at 8 mg NH_3-N / dL rumen fluid. This is higher than the concentration reported in Table 8.3 ranging from 3.86 (T4) to 5.15 mg/ 100 ml rumen fluid (T1). The lack of increase in the ruminal NH_3-N with increased CP intake could indicate the protein binding effect of *L. cuneata* CT reported by Waghorn (1996) and Puchala *et al*. (2005). These authors reported an increased intestinal amino acid (AA) absorption in sheep receiving diets consisting of *L. cuneata*. The increase in intestinal AA absorption could enhance the growth rate and wool production of sheep receiving diets containing CT (Shewangzaw, 2016).

Total volatile fatty acid concentration in sheep was not affected ($P>0.05$) by the experimental treatments. However, increasing the level of *L. cuneata* in experimental treatments decreased ($P<0.05$) the molar proportion of acetic acid with a simultaneous increase in the propionic acid and butyric acid concentrations. Hammond *et al*. (2013) stated that higher feed intakes resulted in shorter mean rumen retention times, consequently decreasing the extent of rumen fermentation compared to lower feed intakes. Decreased ruminal retention times could decrease CH_4 yield due to a shift in fermentation pathways towards more propionate production and thus less CH_4 production per unit of DMI (Janssen, 2010). Dumeric *et al*. (2017) reported that feeding diets containing CT to sheep affected ruminal fermentation and resulted in a reduction ($P<0.05$) of ruminal fibrolytic bacteria. This supported the reduction in the molar proportion of acetate with increased levels *L. cuneata* in the experimental treatments (Table 8.3). The decreased NDF and increased NFC concentration in the experimental diets (Table 8.1) with increased levels of *L. cuneata* favoured the formation of propionate and butyrate, proportionally as a percentage of total VFA, in the ruminal fluid (Table 8.3). This data supports data reported by Hindrichsen *et al*. (2004) for diets high in NFC concentrations. Friggens *et al*. (1998) stated that the sugar and pectin content in the NFC concentration of feedstuffs are preferential to the formation of butyrate in the rumen at the expense of propionate. This could explain the relative high molar proportions of butyrate in the current study (Table 8.3). The decrease ($P<0.05$) in the A:P ratio from T 1 to T 3 and T 1 to T

4 is consistent with the reduction in CH_4 production reported in Table 8.2. The formation of propionate in the rumen serves as a competitive pathway for metabolic H_2 to CH_4 production (Moss *et al*., 2000). Yang *et al*. (2016) reported that supplementing diets with tannic acid increased the propionate concentration and decreased the ruminal A:P ratio in rumen fluid. These results are consistent with results for the present study reported in Table 8.3.

Conclusion

Results from this study suggest that *L. cuneata* has the potential to reduce CH_4 emissions from sheep fed a sub-tropical hay in addition to possible benefits of improved production. Substituting *E. curvula* hay with *L. cuneata* hay improved diet digestibility, and led to increased concentrations of CP, NDF and NFC. The increased intake of diets containing *L. cuneata* compared to *E. curvula* indicated that the potential adverse effects of CT in the *L. cuneata* used in the study were relatively low. Substituting *E. curvula* hay with 60% *L. cuneata* on a DM basis resulted in the highest CH_4 reduction of 21.4% compared to a 100% *E. curvula* diet. Further research is necessary to identify the optimal inclusion level of *L. cuneata* in a sub-tropical hay based diet and to explore the possible long term feeding effects on the production potential of ruminants.

Acknowledgements

This study forms part of a larger project jointly funded by the Red Meat Research and Development Trust of South Africa and the National Research Foundation of South Africa. The Animal Ethics Committee of the University of Pretoria approved all experimental protocols (ECO18-14) before commencement of the study.

References

AFRC, 1993. Energy and protein requirements of ruminants. CAB International. Wallingford.

Aitchison, E.M., Gill, M., Dhanoa, M.S. and Osbourn, D.F., 1986. The effect of digestibility and forage species on the removal of digesta from the rumen and the voluntary intake of hay by sheep. Br. J. Nutr. 56, 463 – 472.

Animut, G., Puchala, A., Goetsh, A.L., Patra, A.K., Sahlu, T., Varel, V.H. and Wells, J., 2008. Methane emission by goats consuming different sources of condensed tannins. Anim. Feed Sci. Technol. 14, 228 – 241.

AOAC., 2000. Association of Official Analytical Chemists. Official method of analysis. 17ed. Association of Official Analytical Chemists, Rockville, MD, USA.

Bell, M., Eckard, R., Moate, P.J. and Yan, T., 2016. Modelling the effect of diet composition on enteric methane emissions across sheep, beef cattle and dairy cows. Animals. 54 (6), 27 – 43.

Benchaar, C., Pomar, C. and Chiquette, J., 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. Can. J. Anim. Sci. 81, 563 – 574.

Bhatta, R., Shinde, A.K., Vaithiyanathan, S., Sankhyan, S.K. and Verma, D.L., 2002. Effect of polyethelyne glycol 6000 on nutrient intake, digestion and growth of kids browsing *Prosopis cineraria*. Anim. Feed Sci. Technol. 123/124, 365 – 377.

Broadhurst R.B. and Jones, W.T., 1978. Analysis of condensed tannins using acidified vanillin. J. Sci. Food Agric. 29, 788 -794.

Broderick, G.A. and Kang, J.H., 1980. Automated simultaneous determination of ammonia and total amino acids in ruminal fluid and *in vitro* media. J. Dairy Sci. 63, 64 – 75.

Carulla, J.E., Kreuzer, M. and Hess, H.D., 2005. Supplementation of *Acacia mearnsii* tannins decreases methanogenesis and urinary nitrogen in forage-fed sheep. Crop and Past. Sci. 56, 961 – 970.

Chaves, A.V., Waghorn, G.C., Brookes, I.M. and Woodfield, D.R., 2006. Effect of maturation and initial harvest dates on the nutritive characteristics of ryegrass (*Lolium perenne* L.) Anim. Feed Sci. Technol. 127, 293 – 318.

Du Toit, C.J.L., Van Niekerk, W.A. and Meissner, H.H., 2013. Direct greenhouse gas emissions of the South African small stock sectors. S. A. J. Anim. Sci. 43 (3), 340 – 361.

Dumeric, Z., Ramirez-Restrepo, C.A., Gardiner, C., O'Neil, C.J., Hussein, E. and Vercoe, P.E., 2017. Differences in nutrient concentrations, *in vitro* methanogenic potential and other fermentative traits of tropical grasses and legumes for beef production systems in northern Australia. J. Sci. Food Agric. doi:10.1002/jsfa.8274

Eun, J.S., Fellner, V. and Gumpertz, M.L., 2004. Methane production by mixed ruminal cultures incubated in dual-flow fermenters. J. Dairy Sci. 87, 112-121.

Fox, D. G., Tedeschi, L. O., Tylutki, T. P., Russel, J. B., Van Amburgh, M. E., Chase, L. E., Pell, A. N. and Overton, T. R., 2004. The Cornell net carbohydrate and protein system model for evaluating herd nutrition and nutrient excretion. Anim. Feed Sci. Technol. 112, 29 – 78.

Friggens, N. C., Oldham, J. D., Dewhurst, R. J. and Horgan, G., 1998. Proportions of volatile fatty acids in relation to the chemical composition of feeds based on grass silage. J. Dairy Sci. 81, 1331–1344.

Gemeda, B.S., 2014. Use of selected tropical feeds and additives as modulators of rumen fermentation and methanogenesis in ruminants. PhD Thesis. University of Pretoria.

Gemeda, B.S. and Hassen, A., 2015. Methane production of two roughage and total mixed rations as influenced by cellulase and xylanase enzyme addition. Sci. Agric. 72 (1), 11 – 19.

Hammond, K.J., Burke, J.L., Koolaard, J.P., Muetzel, S., Pinares-Patino, C.S. and Waghorn, G.C., 2013. Effects of feed intake on enteric methane emissions from sheep fed fresh white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) forages. Anim. Feed Sci. Technol. 179, 121 – 132.

Hart, K.J., Yanes-Ruiz, D.R., Martin-Garcia, A.L. and Newbold, C.J., 2012. Sheep methane chambers at Aberystwyth University (UK) and CSIC (Spain). In: Technical manual on respiration chamber design. Ed Pinarez-Patino, C., Hunt, C., Martin, R., West, J., Lovejoy, P., Waghorn, G. Ministry of Agriculture and Forestry, New Zealand.

Hart, K.J., Yanez-Ruiz, D.R. Duval, S.M., McEwan, N.R. and Newbold, C.J., 2008. Plant extracts to manipulate rumen fermentation. Anim. Feed Sci. Technol. 147, 8 – 35.

Hassanat, F. and Benchaar, C., 2013. Assessment of the effect of condensed (acacia and quebracho) and hydrolysable (chesnut and valonea) tannins on rumen fermentation and methane production *in vitro*. J. Sci. Food Agric. 93, 332 – 339.

Hindrichsen, I.K., Wettstain, H.R., Machmuller, A., Solvia, C.R., Bach Knudsen, K.E., Madsen, J. and Kreuzer, M., 2004. Effects of feed carbohydrates with contrasting properties on rumen fermentation and methane release *in vitro*. Can. J. Anim. Sci. 84, 265 – 276.

Hirstov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B. and Tricarico, J.M., 2013. Special topics – mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91, 5045 – 5069.

Janssen, P.H., 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. Anim. Feed Sci. Technol. 160, 1 – 22.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483-2492.

Jones, W.T. and Mangan, J.L., 1977. Complexes of the condensed tannins of sainfoin (*Onobrychis viciifolia* Scop.) with fraction 1 leaf protein with submaxillary mucoprotein, and their reversal by polyethylene glycol and pH. J. Sci. Food Agric. 28, 126 – 136.

Kanjanapruthipong, J. and Leng, R. A., 1998. The effects of dietary urea on microbial populations in the rumen of sheep. Amer. J. Anim. Sci. 11 (6), 661 – 672.

Kennedy, P.M. and Charmley, E., 2012. Methane yield from Brahman cattle fed tropical grasses and legumes. Anim. Prod. Sci. 52, 225 – 239.

McDonald, P., Edwards, R.A., Greenhalg, J.F.D., Morgan, C.A., Sinclair, L.A. and Wilkinson, R.G., 2011. Animal nutrition. 7th ed. London: Prentice Hall.

Min, B.R., Barry, T.N., Attwood, G.T. and McNabb, W.C., 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: A review. Anim. Feed Sci. Technol. 106, 3 – 19.

Moore, K.J. and Jung, H.G., 2001. Lignin and fibre digestion. J. Range Manage. 54, 420 – 430.

Moss, A.R., Jouany, J.P., Newbold, J., Agabriel, J. and Givens, I., 2000. Methane production by ruminants: its contribution to global warming. Annales De Zootechnie. 49, 231 – 253.

Muetzel, S. and Clark, H., 2015. Methane emissions from sheep fed fresh pasture. N. Z. J. Agric. Res. 58, 472 – 489.

Newbold, C.J., Lopez, S., Nelson, N., Ouda, J.O., Wallace, R.J., and Moss, A.R., 2005. Propionate precursors and other metabolic intermediates as possible alternative electron acceptors to methanogenesis in ruminal fermentation *in vitro*. Br. J. Nutr. 94, 27-35.

Norton, B.W., 2003. Tree legumes as dietary supplements for ruminants. Unasylva 51 (200), 25 – 32.

Ominski, K.H., Boadi, D.A. and Wittenberg, K.M., 2006. Enteric methane emissions from background cattle consuming all forage diets. Can. J. Anim. Sci. 83, 393 – 400.

Osuji, P.O., Nsahlai, I.V. and Khalilil, H., 1993. Feed evaluation. ILCA manual 5. ILCA (International livestock centre for Africa), Addis Ababa, Ethiopia.

Patra, A.K. and Saxena, J., 2010. A new perspective on the use of plant secondary metabolites to inhibit methanogenesis in the rumen. Phytochemistry. 71, 1198–1222.

Patra, A., Tanso, P., Minseok, K. and Zhongtang, Y., 2017. Rumen methanogens and mitigation of methane emission by anti-methanogenic compounds and substances. J. Anim. Sci. Biotech. 8, 13 – 31.

Pelchen, A. and Peters, K.J., 1998. Methane emissions from sheep. Small Rum. Res. 27, 137 – 150.

Puchala, R., Animut, G., Patra, A.K., Detweiler, G.D., Wells, J.E., Varel, V.H., Sahlu, T. and Goetsch, A.L., 2012. Effects of different fresh-cut forages and their hays on feed intake, digestibility, heat production, and ruminal methane emission by Boer x Spanish goats. J. Anim. Sci. 90, 2754 – 2762.

Puchala, R., Min, B.R., Goetsch, A.L. and Sahlu, T., 2005. The effect of a condensed tannin-containing forage on methane emission by goats. J. Anim. Sci. 83, 182 – 186.

Reed, J.D., 1995. Nutritional toxicology of tannins and related polyphenols in forage legumes. J. Anim. Sci. 73. 1516 – 1528.

Reid, R.L., Jung, G.A., Cox-Ganser, J.M., Rybeck, B.F. and Townsend, E.C. 1990. Comparative utilization of warm- and cool-season forages by cattle, sheep and goats. J. Anim. Sci. 68, 2986 – 2994.

Samuels, M. L. and Wittmer, J. A., 2003. Statistics for the life sciences. Upper Saddle River NJ., Prentice Hall.

SAS., 2015. Statistical Analysis System user's guide: Statistics version 9.1.3. SAS institute Inc, Cary, NC, USA.

Scholtz, M.M., McManus, C., Okeyo, A.M. and Theunissen, A., 2011. Opportunities for beef production in developing countries of the Southern hemisphere. Livest. Sci. 142, 195 – 202.

Shewangzaw, A., 2016. Effect of dietary tannin source feeds on ruminal fermentation and production of cattle: A review. J. Anim. Feed Res. 2, 45 – 55.

Sinclair, L.A., Hart, K.J., Wilkinson, R.G. and Huntington, J.A., 2009. Effect of inclusion of whole-crop pea silages differing in their tannin content on the performance of dairy cows fed high or low protein concentrates. Livest. Sci. 124, 306 – 313.

Tan, H.Y., Sieo, C.C., Abdullah, N., Liang, J.B., Huang, X.D. and Ho, Y.W., 2011. Effects of condensed tannins from Leucaena on methane production, rumen fermentation and populations of methanogens and protozoa *in vitro*. Anim. Feed Sci. Technol. 169, 185 – 193.

Terrill, T.H., Rowan, A.M., Douglas, G.B. and Barry, T.N., 1989. Determination of extractable and bound condensed tannin concentrations in forage plants, protein concentrate meals and cereal grains. J. Sci. Food Agric. 58, 321 – 329.

Van Soest P.J., Robertson, P.J. and Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583 – 3597.

Waghorn, G., 1996. Condensed tannins and nutrient absorption from the small intestine. Proc of the 1996 Canadian Society of Animal Science Annual Meeting, Lethbridge, Canada (Rode L.M., ed.). 175 – 194.

Wasserman, V.D., 1981. Temperate pasture legumes for poor soils. Farming in S. Afr. E 4.6

Webb, E. C., 1994. Synthesis of long chain fatty acids in ruminants and their effects on meat quality. Ph.D thesis, University of Pretoria. South Africa.

Woodward, S.L., Waghorn, G.C., Lassey, K.R. and Laboyrie, P.G., 2002. Does feeding sulla (*Hedysarum coronarium*) reduce methane emissions from dairy cows? Proc. N.Z. Soc. Anim. Sci. 62, 227 – 230.

Yang, K., Wei, C., Zhoa, G.Y., Xu, Z.W. and Lin, S.X., 2017. Effects of dietary supplementing tannic acid in the ration of beef cattle on rumen fermentation, methane emission, microbial flora and nutrient digestibility. J. Anim. Physiol. Anim. Nutr. 101, 302 – 310.

Chapter 9

General conclusion

Livestock production in South Africa and other developing countries is under increasing pressure to produce high quality products in an environmentally responsible and sustainable manner. South Africa committed to greenhouse gas reduction targets below the business as usual scenario of 34% by 2020 and 42% by 2025 (DEA, 2015). In contributing to reduction targets the agricultural sector needs to consider food security for an ever-growing population while reducing GHG emissions from production practices.

The livestock sector in South Africa is based on a unique combination of commercial and emerging or communal production systems. Commercial systems, and in particular intensive and semi-intensive systems, have a higher production efficiency compared to communal and subsistence systems that are mainly based on extensive production systems. Approximately 70% of the available agricultural land in South Africa is only suitable for extensive livestock production systems. These extensive production systems often have a poor nutritional status for livestock characterized by highly lignified, low digestible feed from native rangeland and crop residues often with low energy and nitrogen (N) concentrations. These conditions limit the productivity of extensive ruminant livestock in tropical and sub-tropical regions (Goel and Makkar, 2012). Ruminants fed on low quality forages represent a significant loss of dietary energy to CH_4 production that could potentially be redirected towards production of milk, meat and fibre (Eckard *et al.*, 2010). Johnson and Johnson (1995) reported a loss of 2 to 12% of dietary energy in ruminants fed high fibre pastures through CH_4 production.

The quantification of livestock emissions is necessary due to the requirements for national auditing and reporting of emissions under the Kyoto protocol and international agreements. It is important to generate accurate country specific greenhouse gas (GHG) baseline figures to develop South Africa's capacity to understand and reduce GHG emissions from the livestock sector. The aim of this research was to investigate and develop country specific greenhouse gas emission factors for all South African livestock sectors taking into consideration the uniqueness of the South African scenario and to identify possible greenhouse gas mitigation strategies for extensive livestock production systems.

The inventory calculations (as described in Chapter 2 to 5) were based on the Australian national greenhouse account's National Inventory Report (ANIR, 2010) which contained both Australian country-specific and IPCC default methodologies and emission factors. A IPCC Tier 2 approach was adopted for all major livestock sectors in accordance with the IPCC good practice requirements (IPCC, 2006). The inventory was compiled on a provincial basis to reduce errors associated with averaging input data across areas with environmental, physical, and managerial differences. Livestock activity data was based on 2010 population data from governmental and commercials agricultural sources cross references with production data.

In Chapter 2 it is reported that cattle contributed an estimated 964 Gg or 73% of the direct livestock GHG emissions in South Africa. Commercial beef cattle on natural rangeland were the major contributors to CH_4 emissions followed by emerging/ communal beef cattle, dairy cattle, and feedlot cattle with 527 Gg, 276 Gg, 130 Gg and 30 Gg, respectively. The estimated enteric

emission factors for South African cattle were higher across all categories compared to other developing countries such as Brazil and India, which have smaller animals fed on lower quality diets. Enteric emission factors for feedlot cattle were comparable to feedlot emission factors from developed countries with similar cattle types.

The calculated GHG emissions from the South African small stock sectors is reported in Chapter 3. The sheep industry (mutton and wool) contributed an estimated 167 Gg of methane and the goat industry 40.7 Gg with an a combined 16% of the total national methane emissions. The commercial sheep industry contributed and estimated 91% of sheep emissions whereas 56% of goat emissions originated from the emerging and communal farming sectors. Emerging/ communal sheep emissions were estimated to be 28% lower than those of commercial sheep (Chapter 3). The lower emission factors of emerging/ communal sheep were mainly due to lower live weights, lower quality diets and lower daily intakes. South African emission factors developed in the study for small stock were not comparable to other developing countries such as Brazil, India, China, and Asia. These differences were likely due to differences in live weights, flock age structures, breed types and differences in diet quality.

The private game ranching industry occupies approximately 17% (20 500 000 ha) of South Africa's total land area which equates to 24% of South Africa's 84 million hectares of grazing land (Dry, 2011). Game ranching has become an organized and recognized commercial industry (Van der Waal and Dekker, 2000) and is ranked the fifth largest agricultural sector in South Africa (Van Rooyen, 2013). Previous GHG inventories did not include privately owned game as an emission source. In the present study, privately owned game was identified as a key CH_4 emission source (Chapter 4) contributing 132 Gg of CH_4 to the national livestock inventory. The emission factors per individual animal were calculated based on energy requirements and provincial contributions were estimated based on habitat and average carrying capacity of game farms per province. Emission factors calculated in the present study were higher than emissions calculated for certain species by Curtzen *et al*. (1986). The emission factors calculated by Curtzen *et al*. (1986) were based on animals with lower live weights and gross energy intakes than when compared to those reported in the present study.

The GHG contribution from non-ruminant and hindgut fermenter livestock in South Africa as reported in Chapter 5 is minor compared to ruminant GHG emissions. Research on the quantification of emissions from these livestock categories is limited and most GHG emissions from pigs, equines and poultry are based on IPCC default values. Non-ruminant livestock are responsible for an estimated 26 Gg of South African national livestock emissions in 2010 (Chapter 5) with ostriches being the largest contributors followed by pigs, horses, poultry, and other equines with 31.1%, 30.6%, 18.9%, 12.8% and 6.4% respectively of the total non-ruminant CH_4 emissions. The poultry industry was the largest direct N_2O emission producer of the non-ruminant livestock industries with an estimated 2.3 Gg or 92% of the total N_2O emission originating from pigs, horses, and poultry.

Characterization of available feed resources in terms of chemical composition and methane production potential is essential to identify feed sources and plant species or varieties with low methane production potential. Such screening work is necessary in identifying potential nutritional GHG mitigation strategies. A range of perennial grass species typical to transitional rangeland in South Africa were evaluated for *in vitro* methane production potential in Chapter 6. The results showed that *in vitro* methane production varied between the selected perennial sub-tropical grass species. The variation between species allows for the potential to identify and select species with

a lower enteric methane production potential. *Panicum maximum* and *Eragrostis curvula* were two of the species which produced the lowest *in vitro* methane production and presented with CP concentrations and IVOMD values above the average for the species evaluated in the study.

The effect of rangeland ecological status as influenced by management practices, used to determine the condition of rangeland, on the *in vitro* methane production potential of grazing livestock was also reported in Chapter 6. The results from the study indicated that rangeland dominated by Decreaser grass species should have a greater potential for livestock production and a lower CH_4 production intensity (unit CH_4 produced per unit of livestock product) when compared to Increaser I and Increaser II species dominated rangeland.

Improved pasture management has been proposed as a viable mitigation strategy to reduce the CH_4 production intensity of livestock in extensive production systems. McCaughey *et al*. (1999) reported a 20% reduction in the methane production per unit basis of livestock product through improved forage quality. South African livestock and game producers are increasingly incorporating adapted improved grass species into production systems to improve the efficiency and flexibility of production. In the present study, the effect of N fertilization on the nutritional quality and *in vitro* methanogenic potential of commonly used improved pasture species in South Africa was evaluated (Chapter 7). The study showed significant differences in nutrient composition, *in vitro* digestibility, and *in vitro* gas production characteristics among key South African improved C3 (temperate) and C4 (sub-tropical) perennial grass species. Between species differences were found for 24-hour methane production in C4 and C3 species but these differences diminished at the 48-hour incubation period. The data suggested that the stage of physiological development of forages will have a greater influence on the methanogenic potential of forages compared to the effect of nitrogen fertilizer application.

Several researchers have reported reduced CH_4 emissions from ruminants consuming forages containing condensed tannins (CT), determined *in vitro* and *in vivo* from cattle and goats (Woodward *et al*., 2002; Min *et al*., 2003; Animut *et al*., 2008). Puchala *et al*. (2012) identified *Lespedeza cuneata* as a perennial legume high in condensed tannins and Wasserman (1981) stated that *L. cuneata* is well adapted to low pH marginal agricultural soils in South Africa. This makes the use of *L. cuneata* a viable mitigation strategy in extensive ruminant production systems. Chapter 8 reports on an *in vivo* study with sheep where the effect of substituting an *E. curvula* hay diet with different levels of *L. cuneata* hay on DMI, digestibility and enteric methane emissions were investigated employing the open circuit respiration chmber technique. The results from this study suggested that *L. cuneata* has the potential to reduce CH_4 emissions from sheep fed a sub-tropical hay diet in addition to possible benefits of improved production. Substituting *E. curvula* hay with *L. cuneata* hay improved diet digestibility, and led to increased concentrations of CP, and NFC and decreased NDF concentrations of diets. The increased intake of diets containing *L. cuneata* compared to *E. curvula* indicated that the potential adverse effects of CT in the *L. cuneata* used in the present study were relatively low. Substituting *E. curvula* hay with 60% *L. cuneata* hay on a DM basis resulted in the highest CH_4 reduction of 21.4% compared to a 100% *E. curvula* diet. The daily CH_4 emissions in the present study were comparable to values reported in literature as well as to predicted daily CH_4 values for South African sheep in commercial operations ranging from 22.6g/d to 29.0 g/d developed using Tier 2 country specific emission factors developed in Chapter 3.

From the studies carried out in this thesis it can be concluded that:

1. The IPCC default emission factors for Africa underestimate the GHG emission from South African livestock.
2. Commercial and communal emerging beef cattle are the major GHG emission contributors in the South African livestock sector.
3. Privately owned game is a key GHG emission source in the South African livestock sector and need to be included in agricultural GHG emissions inventories.
4. There is scope to identify and select for perennial grass species in transitional rangeland areas of South Africa with a low methanogenic potential without negatively affecting livestock production.
5. Rangeland in good condition dominated by Decreaser grass species should have a greater potential for livestock production and a lower CH_4 production intensity (unit CH_4 produced per unit of livestock product) when compared to Increaser I and Increaser II species dominated rangeland.
6. Nitrogen fertilization of improved perennial grass species commonly utilized in South African livestock production systems did not have an effect on the methanogenic potential of the species at a constant physiological age but the fertilization improved the nutritional quality of grass species.
7. *Lespedeza cuneata* has the potential to reduce CH_4 emissions by 21% and possibly increase production from sheep when included in diets based on sub-tropical hay at levels of 60% and higher on a DM basis.

Critical evaluation

A detailed uncertainty analysis of all developed GHG emission factors would improve the reliability of the data and results presented in chapter 2 to chapter 5 in the thesis. The accuracy of commercial and communal/ emerging livestock population data remains the largest source of uncertainty in developing national GHG inventories. While implementing a Tier 2 approach to the development of livestock GHG emissions reduced the uncertainty of emission values compared to previous national GHG emissions inventories, there is still scope to improve the accuracy of the estimated livestock emissions factors. Improvement of the livestock activity data needed for the development of emission factors is critical to improve the accuracy of emission factors and effectively evaluate possible GHG mitigation strategies.

At present, there is very limited data on the commercial/ emerging livestock populations in terms of population numbers, herd/ flock structure, animal live weight, daily intake, diet quality and reproductive efficiency on both a national and provincial or regional basis. Similar data gaps exist for commercial livestock production but to a lesser extent.

The management of livestock manure plays an important role in emissions generated from manure. There is currently very limited data on the manure management systems in both commercial and communal livestock production systems. Development of country specific manure emission factors for all livestock categories through experimental techniques would improve the accuracy of the inventories and aid South Africa in moving toward a Tier 3 inventory as required by the IPCC good practice guidelines.

There is a lack of nutritional data on forage quality on a regional basis across different seasons. Incorporating improved and updated data on the nutritional value of livestock diets as it varies across different seasons would improve the accuracy of estimated emission factors especially for extensively produced livestock which is the major contributors to national methane emissions. It is also important to incorporate the carbon sequestration ability of South African rangelands to give a true reflection of the carbon efficiency of livestock production systems.

Forage quality vary greatly within and between different grass species and between seasons. The current study evaluated the effect of different species common to transitional rangeland in South Africa on *in vitro* methane production focusing only on one physiological age, full bloom. These results do not account for possible variation between species during early and mid-developmental stages. Perennial grass species mature at different rates and it is possible that differences between species might have been lost by only evaluating species at a mature stage of development. The current study also did not evaluate seasonal differences between species as well as regional effects on forage quality.

The use on nitrogen fertilizer to improve the nutrient quality and reduce the methanogenic potential of improved pastures species could be evaluated at different moisture regimes. In this study, the trial was run at field capacity and plants did not experience moisture stress. The evaluation of the effect of physiological development under different N fertilization regimes under field conditions would also improve the outcome of the study and give producers insight on the effect different rotational grazing periods on the methanogenic potential of the effected improved pastures.

It is recommended to follow up the *in vitro* experiments by *in vivo* experiments to insure *in vivo* efficacy of screening results and possible adaptation of the results as mitigation strategies.

The highest potential for CH_4 emission reductions are with extensive grazing systems due to the lower basal efficiency of these systems compared to more intensive production systems. The use of *L. cuneata* has been shown to be a viable mitigation strategy to incorporate into extensive production systems. In this study, it was shown that the incorporation of *L. cuneata* at a substitution rate of 60% of DM will reduce CH_4 emissions by as much as 20% but the method of CH_4 reduction is unclear. The study should be duplicated incorporating diets containing polyethylene glycol (PEG) to ascertain if the reduction in CH_4 emissions are due to the CT concentration in the diet or due to nutritional factors, differences in degradation rates, and ruminal retention rates.

Future research

Significant reduction in enteric methane emissions from extensive livestock production systems will require greater time and resource investment. The following research is suggested to improve the accuracy of livestock emission factors and to develop and evaluate possible GHG mitigation strategies applicable to South African livestock production systems:

1. Development of survey techniques to improve livestock population and activity data across all production systems on a regional and national level.
2. Identification and evaluation of methods best suited to quantify GHG emissions from South African livestock under different production environments.
3. Development of specie specific methane emission factors incorporating variation in feed quality through *in vivo* experimentation.
4. The quantification of the carbon sequestration ability of natural rangeland under different conditions as well as the effect of improved pasture management and the incorporation of cultivated pastures on the carbon sequestration potential of livestock production systems.
5. Development of species, regional and production system specific carbon life cycle analysis (LCA's) to be able to evaluate the carbon efficiency of production systems and to be able to evaluate mitigation protocols.
6. The optimal proportion of *Lespedeza cuneata* in a diet of sub-tropical grass required to achieve significant reduction in CH_4 yield is unknown and needs to be further investigated.
7. The identification and evaluation of novel feed additives or combinations of feed additives to reduce enteric and manure methane emissions from livestock in intensive production systems. It is important to determine the time period and efficacy of the identified additives before ruminal microflora adaptation occurs as well the possible effects of supplements of livestock product quality.

References

Animut, G., Puchala, A., Goetsh, A.L., Patra, A.K., Sahlu, T., Varel, V.H. and Wells, J., 2008. Methane emission by goats consuming different sources of condensed tannins. Anim. Feed Sci. Technol. 14, 228 – 241.

ANIR, 2010. Australian National Inventory Report - Australian national greenhouse accounts: National Inventory Report. Department of climate change and energy efficiency, Commonwealth of Australia, Canberra, ACT.

Curtzen, P.J., Aselmann, I. and Seiler, W., 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. Tellus, 38B: 271-284.

DEA, 2015. Department of environmental affairs: South Africa's intended nationally determined contributions (INDC) – discussion document. Pretoria, South Africa.

Dry, G.C., 2011. Commercial wildlife ranching's contribution to a resource efficient. Low carbon, pro-employment green economy. Presentation at the 7th International Wildlife Ranching Symposium, Kimberley, October 2011. South Africa.

Eckard, R.J., Grainger, C. and De Klein, C.A.M., 2010. Options for abatement of methane and nitrous oxide from ruminant production. Livest. Sci. 130, 47 – 56.

Goel, G. and Makkar, H.P.S., 2012. Methane mitigation from ruminants using tannins and saponins, a status review. Trop. Anim. Health Prod. 44, 729 – 729.

IPCC, 2006. IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National greenhouse Gas Inventories Programme. Eds: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K., Published: IGES, Japan.

Johnson, K.A. and Johnson, D.E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483-2492.

McCaughey, W.P., Wittenberg, K. and Corrigan, D., 1999. Impact of pasture type on methane production by lactating beef cows. Can. J. Anim. Sci. 79, 221 – 226.

Min, B.R., Barry, T.N., Attwood, G.T. and McNabb, W.C., 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: A review. Anim. Feed Sci. Technol. 106, 3 – 19.

Puchala, R., Animut, G., Patra, A.K., Detweiler, G.D., Wells, J.E., Varel, V.H., Sahlu, T. and Goetsch, A.L., 2012. Effects of different fresh-cut forages and their hays on feed intake, digestibility, heat production, and ruminal methane emission by Boer x Spanish goats. J. Anim. Sci. 90, 2754 – 2762.

Van der Waal, C. and Dekker, B., 2000. Game ranching in the Northern Province of South Africa. S. Afr. J Wildl. Res. 30 (4), 151-156.

Van Rooyen, L., 2013. Game ranches unite to influence policy. Farmers Weekly, 9 April 2013, South Africa.

Wasserman, V.D., 1981. Temperate pasture legumes for poor soils. Farming in S. Afr. E 4.6

Woodward, S.L., Waghorn, G.C., Lassey, K.R. and Laboyrie, P.G., 2002. Does feeding sulla (*Hedysarum coronarium*) reduce methane emissions from dairy cows? Proc. N.Z. Soc. Anim. Sci. 62, 227 – 230.