GREENHOUSE GAS EMISSIONS FROM BEEF CATTLE GRAZING SYSTEMS IN FLORIDA

By

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To God, the best Agricultural Engineer I know, and to my family

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Pastoral systems are of crucial importance for the economy of Florida. The cattle industry in this state is composed mostly of cow-calf operations that rely heavily on grazing systems using tropical grass species such as bahiagrass (*Paspalum notatum* Flugge). Agricultural operations are also an important source of greenhouse gas (GHG) emissions. Although the scientific community, governmental organizations and public opinion have increased their interest in environmental issues related to the production of food, little is known about the emission of GHG from beef cattle in Florida. The objectives of this study were to estimate GHG emissions (carbon footprint) from a typical low- input cow-calf operation in Florida, examine the model used for estimation of animal methane (CH_4) production and measure animal CH_4 production using the sulfur hexafluoride (SF_6) tracer technique. The model developed by IPCC with emission factors specific for the USA or Florida was used when available from EPA. The greatest source of GHG in the cow- calf operation studied was from enteric fermentation followed by manure. A sensitivity analysis of the model used for estimating enteric CH_4 production was performed with Morris, Fourier Amplitude Sensitivity Test and the vary- one- at- a- time methodologies. All analysis showed that average daily gain was the most important factor influencing the model's output for growing animals independent of feed. A field

experiment was carried out with three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) of animals grazing bahiagrass. Forage quantity and nutritive value were measured, as well as animal performance. Production of CH_4 was measured using the SF_6 technique. No effect of treatment was found in CH_4 emissions or in other animal variables. Emissions averaged 393 g CH_4 $animal^{-1}$ day^{-1}. This was the first CH_4 measurements for grazing beef cattle in Florida. Based on our results the IPCC Tier 2 and Tier 1 approaches seem to underestimate emissions of CH_4 by grazing cattle, with values of 121 and 145 g CH_4 $animal^{-1}$ day^{-1}, respectively. Due to the great importance of agriculture in Florida's economy, it is essential to obtain more information about emissions from different agriculture-related sources. This information may help not only to improve model use but also to provide a better understanding of alternative management approaches that can reduce or avoid GHG emissions.

CHAPTER 1
CARBON FOOTPRINT ESTIMATION

Literature Review

Changes in climate have become increasingly important to society. In 1998, the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO) instituted a scientific body responsible for reviewing scientific, social, economic, and technical information regarding climate change, called Intergovernmental Panel on Climate Change (IPCC). This scientific body is composed of scientists from 195 countries and, because of its intergovernmental character, produces policy-neutral reports. Among its publications, IPCC produces reports to explain the scientific basis of changes in climate, provide information on climate change risk management and adaptation strategies, and establish guidelines for estimating greenhouse gas (GHG) emissions (IPCC, 2013). In the USA, these guidelines are used by the Environmental Protection Agency (EPA) to estimate GHG emissions on a national scale.

According to IPCC (2007a), climate change exists when there is a statistical difference in the average or variability of a climate's property that continues for a decade or more, whether it be natural or originate from anthropogenic actions. There are several factors pointing to the intensification of the greenhouse effect, among which are the increase in air and ocean temperatures, sea level and snow and ice melting (IPCC, 2007a).

Some of the climate modifying agents includes greenhouse gases (GHG), aerosols, solar radiation and surface cover. These factors change the Earth's energy balance positively or negatively and the intensity of this modification is called radiative forcing, measured in W m^{-2}. Anthropogenic activities can be a source of GHG such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and

halocarbons. The concentrations of the first three before the Industrial Revolution and in 2005 are presented in Table 1-1, where we can observe a significant increase in their concentration in the atmosphere. Anthropogenic activities are estimated to have had a positive radiative forcing in the order of 0.6 to 2.4 W m^{-2} since 1750 (IPCC, 2007a).

There are several sources of GHG related to human activities. In 2011, the USA emitted 6,702 million metric tons of CO_2 equivalent. Considering the carbon sequestration occurring in land-use, land-use change and forestry in the US, net emission was 5,797 million metric tons of CO_2 equivalent in 2011. These emissions were composed of different GHG, including 83.7% CO_2, 8.8% CH_4, 5.3% N_2O and 2.2% HFC`s, PFC`s and SF_6. Several economic sectors contribute to the GHG emissions in the USA (Table 1-2). In 2011, agriculture contributed 6.9% of total emissions in the USA (EPA, 2013a).

Agriculture is an important economic activity in Florida. In 2010, agricultural products in Florida were worth 7.81 billion dollars, and cow-calf operations alone accounted for 6.4% of this value. In fact, in January 2012 all cattle and calves in Florida totaled 1,700,000 head, from which 940,000 were beef cattle. In 2011, 890,000 calves were born in Florida (Florida Department of Agriculture and Consumer Services,2012). In this context, it is clear that assessing GHG emissions from the beef industry in Florida is important, and the use of models is of particular importance when analyzing production systems at both a farm scale (Beauchemin et al., 2010) and at larger scales (Storm et al., 2012). Many studies have been conducted regarding estimating GHG emissions from the processes involved in the production of various produces. In fact, when searching for the term “carbon footprint” in all scientific journals covered by ScienceDirect and Scopus, Wiedman

and Minx (2008) there were 42 hits of which 31 happened in 2007. Studying the number of publications on Life Cycle Assessment (LCA) applied to agriculture products between 2001 and 2011, Ruviaro et al. (2012) found a remarkable increase in the number of studies produced particularly after 2007 probably related to governmental and public inquiries regarding anthropogenic influence on global GHG emissions.

The approach used to calculate the carbon footprint can vary greatly. Although some authors define carbon footprint as the amount of CO_2 solely emitted directly and indirectly by an activity or through life stages of products (Wiedman and Minx, 2008), the carbon footprint calculation for agriculture products usually accounts for all of the different GHG involved in their production and transforms them into CO_2-equivalent (CO_2e) according to each gas' global warming potential (GWP) (Röös et al., 2013). These estimations are important to identify the main sources of GHG in a production system and point to possible areas of emission mitigation, as well as energy use inefficiency (Lash and Wellington, 2007). With the increase of society's concern regarding environmental conservation, having to access environmental records also presents a competitive advantage and can drive purchase decisions (Lash and Wellington, 2007).

Considering the importance of cow-calf production in Florida and the necessity to account for the GHG emissions related to this production system in order to satisfy governmental and society's inquiries regarding environmental responsibility, the objective of this study was to quantify the carbon footprint of a cow-calf operation in Florida.

Materials and Methods

Site Description

Buck Island Ranch (BIR) is located in Lake Placid, south-central Florida, northwest of Lake Okeechobee (Figure 1-1). It has been managed by the Archbold Biological Station since 1988 and, as a division of Archbold Expeditions, the MacArthur Agro-ecology Research Center operates at BIR where it promotes long-term ecological research ("Archbold Biological Station," 2013). It also runs a commercial cow-calf operation on an area of 4,200 ha, approximately 3000 Braham cows and 250 Angus bulls (Table 1-4). Management makes use of natural service during 5 to 7 months of the year (usually from January to May, but the breeding season can be extended until June or July). Calves are born during the period of November to March and are sold or transferred to other states at 7 months of age (Figure 1-2). Approximately half of the grazing area is planted to bahiagrass, while the other half is in semi-native pasture. The bahiagrass is occasionally managed with burning.

According to Kottek et al. (2006), the climate in the region is classified as Cfa. In this classification *Cf* stands for climates with warm temperatures and fully humid, with minimum temperatures between -3 and 18 °C. The *a* refers to hot summers with maximum temperatures above 22 °C. There are two soil types occurring the ranch. They are classified as Felda fine sand, which is subjected to frequent flooding, and Ona loamy sand where ground water levels vary between 25 and 100 cm throughout the year (USDA, 1989).

Production records from 1998 to 2008 were considered in this case study. According to the IPCC (2006) guidelines, GHG emissions can be estimated using different levels of data and detail. The methodology used can be classified as Tier 1,

Tier 2 and Tier 3 to characterize increasing level of information needed to estimate GHG emissions and accuracy of the predictions. The higher the Tier used, the smaller the uncertainty.

Livestock categories to be considered in a GHG emission inventory should include all of those which are important to a country or region. Category is described as the animal species and it can be separated into subcategories according to age, type of production and gender (IPCC, 2006). In this study the livestock category considered was cattle, with three subcategories: cows, bulls and calves.

Identification of GHG Sources

The first step in calculating the carbon footprint of a production system involves identifying the sources of GHG involved in the process. The source categories and GHG emission considered in the calculation were identified according to IPCC (2006), while considering specific emission factors available for Florida or the USA in EPA (2013a; 2013b). The sources and GHG emitted at BIR in the period of 1998 to 2008 are delineated in Table 1-8. A brief description follows.

Enteric fermentation. Enteric fermentation refers to a digestive process where the anaerobic microbial population inside the animal's digestive system ferments feed and produces CH_4 as a by-product. Ruminant livestock, including cattle, sheep and goats, have greater rates of enteric fermentation because of their unique digestive system, which includes a large rumen or fore-stomach where enteric fermentation takes place. Production of CH_4 depends on the animal's digestive system and quality and quantity of food (EPA, 2013a). IPCC (2006) only considers emissions from animals older than 7 months of age.

Livestock waste. Manure can be managed in storage or treatment systems or spread on fields in lieu of long-term storage or it can be deposited directly on

grazed lands. The management of livestock manure can produce CH_4 and N_2O. Production of CH_4 is a natural process in anaerobic decomposition of livestock manure (EPA, 2013a). Emissions of N_2O from livestock waste depend on the composition of manure and urine, the type of bacteria involved in the process and the amount of oxygen and water in the manure system. Direct N_2O emissions are produced as part of the N cycle through nitrification and denitrification of the organic N in livestock manure or urine. Indirect N_2O emissions are produced as result of the volatilization of N as ammonia (NH_3) and oxides of nitrogen (NO_x) and runoff and leaching of N during treatment, storage, and transportation (IPCC, 2006).

Pasture burning. Improved and native pastures in BIR are burned primarily between December and February according to a burning schedule. Burns may sometimes occur as late in the year as April in order to enhance biological diversity including endangered and threatened species, reduce fire hazards, mimic natural processes and provide educational and research opportunities (Main and Menges, 1997). When burning fields, CO_2 is not considered to be released since it is largely balanced by the CO_2 that is reincorporated back into biomass via photosynthetic activity within weeks or a few years after burning. Non-CO_2 emissions, particularly carbon monoxide (CO), CH_4, N_2O and other kinds of nitrogen oxides (NO_x) that result from incomplete combustion of biomass in managed grassland are reported (IPCC, 2006). However, since there is no agreement regarding the GWP value and signal for NO_x, this gas was not considered in the evaluation (IPCC, 2006).

Fertilization (with synthetic fertilizer) and liming of pastures and crops. Emissions from these processes include those from manufacturing, storage, transfer and transportation as well as direct emissions of fertilizers and lime applied to the field. The methodology used for accounting for manufacturing, storage and

transportation of fertilizers and lime was developed by Lal (2004). It estimates carbon equivalent emissions by converting the energy or volume involved in the production processes to kg of carbon equivalent (kg CE). After application to the field, fertilizers also release N_2O directly through the microbial processes of nitrification and denitrification or indirectly by volatilization of ammonium (NH_4^+) and nitrate (NO_3^-) or leaching and runoff mainly of nitrate, which can later go through nitrification and denitrification (IPCC, 2006).

Tractor operations. This category includes all activities that require tractor operations such as tilling, planting, harvesting, and application of agrochemicals. These processes mostly release CO_2, but also release CH_4 and N_2O. However, for this paper the methodology used is that developed by the EPA (2005), which considered only CO_2 emissions based on the amount of carbon present in fuels.

Equations

Enteric fermentation

The first step necessary to calculate emissions from enteric fermentation is to determine the different population subcategories. The total number of cows, pregnancy rate, the number of calves and of bulls was obtained from the BIR database. For the seven months after calving, we assumed that the number of lactating cows equaled the number of calves. The cows pregnant in the next breeding season were considered to be lactating. Remaining cows were considered to be neither pregnant nor lactating. Therefore, there were five subcategories of animals considered to emit CH_4 from enteric fermentation: pregnant cows, lactating cows, cows that were both pregnant and lactating, cows that were neither pregnant nor lactating and bulls. Calves are not considered to emit CH_4 from enteric fermentation (IPCC, 2006).

Gross Energy (GE) is the energy the animal needs for maintenance and to perform activities such as lactation. It was considered that all animals were adults and did not perform any work (for example, pulling plows for working the soil, etc.). Therefore, net energy for work and growth were considered zero and REG was not calculated.

$$GE = [(\frac{NEm+NEa+NEl+NEwork+NEp}{REM}) + (\frac{NEg}{REG})] / (\frac{DE}{100})$$

where

GE= gross energy, MJ day^{-1}

NEm= net energy required by the animal for maintenance, MJ day^{-1}

NEa= net energy for animal activity, MJ day^{-1}

NEl= net energy for lactation, MJ day^{-1}

NEwork= net energy for work, MJ day^{-1}

NEp= net energy required for pregnancy, MJ day^{-1}

REM= ratio of net energy available in a diet for maintenance to digestible consumed

NEg= net energy needed for growth, MJ day^{-1}

REG= ratio of net energy available for growth in a diet to digestible energy consumed

DE= digestible energy expressed as a percent of gross energy (percent)

Net energy for work and growth were considered zero. Formulas used to calculate each of the factors involved in GE calculation are as follows:

$$NEm = Cfi \times (weight)^{0.75}$$

where

NEm= net energy required for the animal for maintenance, MJ day^{-1}

Cfi= coefficient, varies for each animal category, MJ day^{-1} kg^{-1}

Weight= live weight of animal, in kg

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

where

NEl= net energy for lactation, MJ day^{-1};

Milk= amount of milk produced, (kg of milk) day^{-1};

Fat= fat content of milk, % by weight.

$$NEp = C_{pregnancy} \times NEm$$

where:

NEp= net energy required for pregnancy, MJ/day^{-1};

$C_{pregnancy}$= pregnancy coefficient;

NEm= net energy required for the animal for mantainance, MJ day^{-1}. The NEm used here was that considering pregnancy.

$$NEa = Ca \times NEm$$

where

NEa= net energy for animal activity, MJ day^{-1};

Ca= activity coefficient corresponding to the animal's feeding situation, dimensionless;

NEm= net energy required for the animal for maintenance, MJ day^{-1}.

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

where

REM= ratio of net energy available in a diet for maintenance to digestible consumed;

DE= digestible energy expressed as a percentage of gross energy.

After the calculation of GE, a daily emission factor for each category was calculated with the formula below.

$$\text{DayEmit} = \left[\frac{GE\ x\ \left(\frac{Ym}{100}\right)}{55.65}\right]$$

where

DayEmit = emission factor, kg CH_4^{-1} head $^{-1}$day^{-1};

GE = gross energy intake, MJ day^{-1};

Ym = CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4 (%);

55.65 = a factor for the energy content of CH_4, MJ (kg CH_4) $^{-1}$

To determine yearly emissions for each category, the formula below was used.

$$\text{Emissions} = \text{DayEmit} \times 365$$

where

Emissions = total emissions in a month for the category, kg CH_4 year^{-1};

DayEmit = emission factor for the category, kg CH_4 head^{-1} day^{-1};

365 = days in the year.

Emissions from enteric fermentation

$$\text{Emissions} = EF_1 \times N$$

where

Emissions = CH_4 emissions from enteric fermentation, kg CH_4 year^{-1};

EF_1 = emission factor for the defined population, kg CH_4 head^{-1} year^{-1};

N = number of animals in the subcategory.

Manure

Manure is a source of both N_2O and CH_4.

Methane

Emission of CH_4 from manure was calculated with the equations below:

$$EF(T) = VS_{(T)} \times [\ Bo_{(T)} \times 0.67 \times \sum S,k\ (MCF_{S,k}/100) \times MS_{(T,S,k)}]$$

where

$EF_{(T)}$ = annual CH_4 emission factor for category T, kg CH_4 animal^{-1} year^{-1};

$VS_{(T)}$ = daily volatile solid excreted for category T, kg dry matter animal^{-1} year^{-1}; for calves, 210 days (7 months) were considered;

$Bo_{(T)}$ = maximum CH_4 producing capacity for manure procedure by livestock category T, m^3 CH_4 (kg of VS excreted)$^{-1}$;

0.67 = conversion factor of m^3 CH_4 to kilogram CH_4;

$MCF_{S,k}$ = CH_4 conversion factors for each manure management system S by climate region k, %;

$MS_{(T,S,k)}$ = fraction of livestock category T's manure handled using manure management system S in climate region k, dimensionless.

Nitrous oxide

N_2O direct emissions

Direct N_2O produced by the manure was calculated with the equations below.

$$N_2Odirect = N_2O\text{-}N_{PR} = F_{PRP} \times EF_{3\ PRP}$$

where

$N_2Odirect$ –N = annual direct N_2O-N emissions produced from livestock waste, kg N_2O-N year^{-1};

N_2O-NPR = annual direct N_2O-N emissions from urine and dung inputs to grazed soils, kg N_2O-N year^{-1};

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N year^{-1};

$EF_{3\ PRP}$ = emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N_2O-N (kg N input)$^{-1}$;

$$F_{PRP} = [(N_{(T)} \times Nex_{(T)}) \times MS_{(T,PRP)}]$$

where

$N_{(T)}$ = number of head of livestock species (category T)$^{-1}$;

$N_{ex(T)}$ = annual average N excretion per head of species (category T)$^{-1}$ (see Table 1-7)

$MS_{(T, PRP)}$ = fraction of total annual N excretion for each livestock species (category T)$^{-1}$ that is deposited on pasture, range and paddock. It was considered 1 in this case because all the excretion was deposited on pasture.

$$N_{ex(T)} = E_N \times weight \times days$$

where

$N_{ex(T)}$ = annual average N excretion per head of species (category T)$^{-1}$;

E_N = excretion of nitrogen, kg day^{-1} (1000 kg) $^{-1}$;

weight = average animal weight during the period, kg;

days = number of days spent in the farm- 365 for cows and bulls and 210 for calves.

To convert the results from kg N_2Odirect–N to kg N_2O, the following formula was used:

$$N_2O = N_2O–Ndirect \times (44/28)$$

N_2O indirect emissions

Indirect emissions of N_2O have two sources calculated separately: volatilization, and leaching and runoff.

To estimate volatilization, the following equation is used:

$$N_2O_{(ATD)}–N = [(F_{ON} + F_{PRP}) \times Frac_{GASM})] \times EF_4$$

where:

$N_2O_{(ATD)}$– N = annual amount of N_2O – N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O – N year^{-1};

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N $year^{-1}$, considered zero in this situation;

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N $year^{-1}$. Same as the one used to calculate direct N_2O emissions from manure management;

$Frac_{GASM}$ = fraction of applied organic N fertilizer material (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_4 and NO_4, kg N volatilized (kg of N applied or deposited) $^{-1}$;

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O – N (kg NH_3-N + NO_x-N)$^{-1}$ volatilized.

To estimate leaching and runoff, the following equation was used:

$$N_2O_{(L)}– N = [(F_{ON} + F_{PRP}) \times Frac_{LEACH–(H)})] \times EF_5$$

where

$N_2O_{(L)–N}$ = annual amount N_2O –N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O –N $year^{-1}$;

$Frac_{LEACH–(H)}$ = fraction of all N added in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg on N added)$^{-1}$;

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O –N (kg N leached and runoff)$^{-1}$.

After that, both N from volatilization and from leaching and runoff are summed, as showed below.

$$N_2Oindirect– N = N_2O_{(L)}– N + N2O_{(ATD)}– N$$

where

N_2Oindirect –N = annual indirect N_2O-N emissions from urine and dung inputs to grazed soils, kg N_2O-N $year^{-1}$.

To convert the results from kg N_2Oindirect –N to kg N_2O, the following formula was used:

$$N_2O = N_2O\text{–Nindirect} \times (44/28)$$

Burning of pasture

The equation used to estimate emissions from pasture burning is shown below.

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3}$$

where

L_{fire}= amount of GHG emissions from fire, tones of each GHG. Indirect GWP for CO was considered 1.9 (IPCC, 2006);

A= area burnt, ha (Table 1-5);

M_B= mass of fuel available for combustion, ton ha^{-1}. It includes biomass, ground litter and dead wood, but when using the Tier 1 method ground litter and dead wood are considered zero except when there is land-use change. The average of above ground mass available for all native or all improved pastures in a specific month was used (Table 1-6).

C_f= combustion factor, dimensionless;

G_{ef}= emission factor, g (kg dry matter burnt)$^{-1}$.

Nitrogen fertilizer

After nitrogen fertilizers are applied to the soil, they release N_2O directly and indirectly, with the same methodology used to calculate N_2O emissions from animal waste.

Direct emissions

$$N_2O_{direct}\text{-}N = N_2O_{imput} = F_{SN} \times EF_1$$

where

N_2O_{direct} –N = annual direct N_2O-N emissions produced from managed soils, kg N_2O-N $year^{-1}$;

N_2O_{imput} –N = annual direct N_2O-N emissions from N inputs to managed soils, kg N_2O-N $year^{-1}$;

N_2O_{direct} –N = annual direct N_2O-N emissions produced from managed soils, kg N_2O-N $year^{-1}$;

N_2O_{imput} –N = annual direct N_2O-N emissions from N inputs to managed soils, kg N_2O-N $year^{-1}$;

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N $year^{-1}$;

EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O-N (kg N input) $^{-1}$.

Indirect emissions

Similarly to manure management, indirect emissions from synthetic N fertilizer application happened through volatilization, and leaching and runoff. To estimate volatilization, the formula used was:

$$N_2O_{(ATD)}\text{– N} = F_{SN} \times Frac_{GASF} \times EF_4$$

where

$N_2O_{(ATD)}$– N = annual amount of N_2O –N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O– N $year^{-1}$;

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N $year^{-1}$;

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, (kg N volatilized) (kg N applied)$^{-1}$;

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O – N (kg NH_3-N + NO_x-N)$^{-1}$ volatilized.

To estimate leaching and runoff, the formula used was:

$$N_2O_{(L)} – N = F_{SN} \times Frac_{LEACH - (H)} \times EF_5$$

where

$N_2O_{(L)}$ –N = annual amount N_2O –N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O–N $year^{-1}$;

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N $year^{-1}$;

$Frac_{LEACH – (H)}$ = fraction of all N added in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N applied)$^{-1}$;

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$.

To estimate total indirect emissions from synthetic fertilizers, emissions from leaching and runoff and volatilization were summed as shown below.

$$N_2Oindirect– N = N_2O_{(L)}– N + N2O_{(ATD)}– N$$

where

N_2Oindirect –N = annual indirect N_2O-N emissions from urine and dung inputs to grazed soils, kg N_2O-N $year^{-1}$.

To convert the results from kg N_2Oindirect –N to kg N_2O, the following formula was used:

$$N_2O = N_2O–Nindirect \times (44/28)$$

Lime

The equation used to estimate the emission from lime (dolomite in this case) after it was applied to the soil was:

$$CO_2\text{-C Emissions} = (M_{dolomite} \times EF_{dolomite})$$

CO_2-C Emissions = annual carbon emissions from lime application, tones C $year^{-1}$

$M_{dolomite}$ = annual amount of calcic dolomite, tons $year^{-1}$;

$EF_{dolomite}$ = emission factor, tons of CO_2 (ton of dolomite lime)$^{-1}$.

Emissions during production, transportation, storage and transfer

Off-farm emissions are an important source of GHG. Many steps are involved before agrochemicals arrive at a farm or ranch. Lal (2004a) developed a methodology to account for GHG emissions from production, transportation, storage and transfer of agrochemicals. In this case study, these emissions are those related to the use fertilizer and lime. For synthetic N fertilizer, the formula used was

Carbon emission = F_{SN} x Equivalent Carbon Emission x (44/28) / 1000

where

Carbon emission = emissions, in kg CO_2e year^{-1};

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N year^{-1};

Equivalent Carbon Emission = C emission in relation to production, packaging, storage and distribution of fertilizers, kg CE (kg N)$^{-1}$.

For the emissions regarding lime's production, transportation, storage and transfer, the equation used was

Carbon emission = $M_{dolomite}$ x Equivalent Carbon Emission x (44/28) / 1000

where

Carbon emission = emissions, in tons CO_2e year^{-1};

$M_{dolomite}$ = annual amount of synthetic fertilizer N applied to soils, kg year^{-1};

Equivalent Carbon Emission = C emission in relation to production, packaging, storage and distribution of fertilizers, kg CE (kg N)$^{-1}$.

Feed concentrate

For feed concentrate, the value of 780 kg CO_2e t^{-1} of feed concentrate according to Casey and Holden (2006). Amount of feed concentrate used is presented on Table 1-7.

Fuel

The formula used to obtain CO_2 emissions from gasoline and diesel used on BIR is shown below. It was considered that the emissions from molasses should be accounted for in sugarcane production and processing, so that emissions regarding the use of molasses are only those ones related to transportation.

$$EmFuel = Fuel \times E_{fuel}$$

where

EmFuel= CO_2e emissions, kg CO_2 $year^{-1}$;

Fuel= amount of fuel used, gallons $year^{-1}$;

E_{fuel}= emission factor, kg CO_2e $gallon^{-1}$.

After emissions were calculated they were expressed as CO_2 equivalent (CO_2e) emitted per unit of live weight produced. The CO_2e is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential. For example, the global warming potential for CH_4 over 100 years is 25. This means that emissions of one metric ton of CH_4 are equivalent to emissions of 25 metric tons of CO_2 (IPCC, 2007b).

Emission factors and other data used for calculating the emissions above described are on Table 1-10 and Table 1-11. Production data including the use of fertilizer, lime and fuel are on Table 1-7.

Results

Results from the carbon footprint calculation from BIR are shown in Figure 1-3 and Figure 1-4. On average, annual emissions in BIR were of 10,470 tons CO_2e $year^{-1}$ and ranged from 8,750 tons CO_2e $year^{-1}$ in 1999 and 12,360 tons CO_2e $year^{-1}$ in 2004. The main source of GHG in this production system is enteric fermentation (55 %), followed by animal waste (27 %), corresponding to 5,770 and 2,790 tons

CO_2e $year^{-1}$, respectively. Application of fertilizer and lime contribute on average with 11 % of total annual emissions in BIR.

In evaluating the variation in amount of GHG emitted yearly at BIR (Figure 1-3) it is possible to determine that the amount of GHG from the main contributors to total emissions (enteric fermentation and animal waste) did not show great fluctuation from one year to the next. The variation observed, however, may be related to the use of management practices such as pasture burning and application of synthetic N fertilizer and lime. The emissions from the use of synthetic N fertilizer and lime can be separated into on farm and pre-farm emission (Figure 1-5). Emissions related to production, transportation, storage and transfer can be very important when considering the use of agrochemicals. In fact, when looking at the emissions from the use of N fertilizer alone, 43% of the GHG emissions occurred before its use. The proportion of emissions occurring during production, transportation, storage and transfer of lime is very significant and accounted for 71% of total emissions connected to its utilization. In a more intensively managed system, where liming and application of fertilizers may be more frequent, the pre-farm GHG production should have greater importance than in the current case study.

The objective of production in BIR is weaned calves, which after 7 months of age are sold or transferred to other regions of the US. Expressing GHG emissions as a function of product originated in a production system can be a useful way to compare different production systems. On average, 22.1 kg CO_2e (kg calf LW)$^{-1}$ was emitted at BIR.

Discussion

In this case study, enteric fermentation was the largest contributor to total GHG emissions in a cow-calf production system (Figure 1-4). This is in accordance

with other studies performed on GHG emissions from beef production systems. Beauchemin et al. (2010) performed a Life Cycle Assessment (LCA) of beef production in western Canada and found that 63% of emissions had their source in enteric fermentation. In the same study, CH_4 and N_2O emissions from beef manure accounted for 28% of total GHG emissions. These results are very similar to those presented in this study, where 55% if emissions came from enteric fermentation and 27% from manure. Basarab et al. (2012) found that enteric fermentation was responsible for 53 to 54% of total emissions when evaluating the full production cycle of a beef herd. When analyzing different beef production systems in Ireland, Foley et al. (2011) found that 46 to 53% of total emissions came from enteric fermentation. It is important to notice that the emissions from enteric fermentation in this study are not directly related to the production of meat since it mainly considers the adult cows. In fact, the productive cows in a full- herd production cycle can account for up to 70% of total GHG emissions (Basarab et al., 2012). Other authors have also highlighted the relevance of GHG emissions coming from animals in the cow-calf production phase, which require high levels of feed for maintenance and low production relative to other production phases in the beef industry (Johnson et al., 2001a).

Management strategies can be used to decrease GHG emissions. The use of growth implants, for example, can reduce the carbon footprint of beef production by 5% (Basarab et al., 2012). Feed management can also strongly influence the carbon footprint. Animals fed high concentrate diets may have less energy lost as CH_4 (Kurihara et al., 1999; Beauchemin and Mcginn, 2005), while low quality feed can result in higher emissions from enteric fermentation (Phetteplace et al., 2001). However, Yan et al. (2010) emphasized that at the farm level it is necessary to consider several aspects associated with maintaining high level production animals

including emissions associated with soil management, feed production and use of fertilizers. This is an important component of more intensively managed systems. Although in this case study the amount of fertilizers and lime applied is not large, it is crucial to acknowledge the importance of GHG emissions occurring before application of these and other products. As Figure 1-5 shows, pre-farm emissions can account for a considerable part of emissions related to the use of agrochemicals, particularly for lime. Although the intensification of management practices can increase total GHG emissions, it can also reduce emissions per unit of product. When analyzing production scenarios varying in management practices in Ireland, Foley et al. (2011) found that inputs required for higher production levels resulted in higher carbon footprint when expressed as tons CO_2e $year^{-1}$. However, when expressed as kg CO_2e $(kg\ beef)^{-1}$, high level production systems had a lower carbon footprint because of associated improvements in fertilizer use and animal growth. Basarab et al. (2012) highlight the fact that time is an important factor when analyzing carbon footprint, particularly regarding the comparison of different production systems. The authors affirm that expressing results of carbon footprint as kg CO_2e $(kg\ beef)^{-1}$ can underestimate the disparity between carbon footprint if a time correction is not made, since higher productivity can be associated with greater animal production per unit of time.

Another relevant aspect of pasture- based production is the ability of the pasture to fix atmospheric carbon (Soussana et al., 2004), and this was not considered in this simulation. The use of pasture as animal feed has several environmental advantages besides potentially reducing the carbon footprint of beef production, including the decrease in emissions from manure and return of nutrients to the soil and making use of the ruminants' ability to convert high fiber material into

high quality protein (Beauchemin et al., 2010; Pelletier et al., 2010). If considering carbon sequestration from pastures, carbon loss in annual cropping and land used in the production of hay the carbon footprint in a beef production system was reduced from 11 to 16% (Basarab et al., 2012). It has also been suggested that best management practices such as intensifying the production system can decrease the carbon footprint through carbon fixation by 15 to 30% while maintaining production levels (Phetteplace et al., 2001).

Using a life cycle assessment (LCA) in western Canada, Beauchemin et al. (2010) found that 83% of GHG emissions in the beef production chain of the region originated in the cow-calf phase. In the US beef production system, the cow-calf phase of beef production was found to be responsible for 76% of GHG emissions (Johnson et al., 2001a). Calves leave BIR with an average weight of 210 kg and, on average, GHG emissions per product are of 22 kg CO_2e (kg calf LW)$^{-1}$. This is in agreement with a study performed in the US using information from Alabama, Texas, Utah, Virginia and Wisconsin where GHG emissions per product were 21 kg CO_2e (kg calf LW)$^{-1}$ (Phetteplace et al., 2001).

The studies conducted by Johnson et al. (2001a) and Beauchemin et al. (2010) demonstrated that most of the GHG emissions in beef production systems (76 and 83%, respectively) come from the cow-calf phase. However, most of the weight gain of animals occurs after they leave the cow-calf phase. Therefore, when expressing the carbon footprint per unit of beef produced as CO_2 e (kg beef)$^{-1}$, higher values are found for the cow-calf phase than for the whole system. If we consider that the animals leaving BIR may achieve 490 kg at slaughter and have 62% of this weight as hot carcass (Miller et al., 1996), we find that emissions for the whole beef production cycle would be of 12 kg CO_2e (kg beef)$^{-1}$ on a live weight basis or 19 kg

CO_2e (kg beef)$^{-1}$ on carcass weight basis. This agrees with many other studies performed in similar production systems. In the US beef production system, the emission of 13 to 16 CO_2e (kg beef)$^{-1}$ on a live weight basis was reported (Johnson et al., 2001a), while Beauchemin et al. (2010) found 13 kg CO_2e (kg beef)$^{-1}$ on a live weight basis and 22 kg CO_2e (kg beef)$^{-1}$ on a carcass weight basis in a case study made for beef production in western Canada. Basarab et al. (2012) reported similar values of 12 to 13 kg CO_2e (kg beef)$^{-1}$ on a live weight basis and 20 to 23 kg CO_2e (kg beef)$^{-1}$ on a carcass weight basis. A range of 22 to 26 kg CO_2e (kg beef)$^{-1}$ on a carcass weight basis was reported (Foley et al., 2011) for scenarios varying in feed management in Ireland. In that study, Foley et al. (2011) found higher total emissions in production systems with higher productivity and therefore input requirements. However, this same scenario presented higher efficiency of fertilizer use and animal performance, resulting in lower emissions relative to beef production. Production efficiency is, therefore, an important aspect to consider when evaluating management strategies to reduce carbon footprint. Expressing carbon footprint relative to produce is a good indicative to production efficiency.

Conclusions

Emissions occurring on pre-farm (before use of specific products in the system evaluated) are relevant and must be accounted for when assessing the carbon footprint of agricultural production systems. In this case study, CH_4 emissions form enteric fermentation were the largest contributor to the carbon footprint. Emissions from BIR varied from one year to another mostly because of management practices such as lime and fertilizer application and pasture burning. On average, BIR emitted 10,500 tons CO_2e year^{-1} and 22 kg CO_2e (kg calf LW)$^{-1}$. These values agree with other similar studies performed in the US and other developed countries.

Table 1-1. Concentration of GHG in the atmosphere before the Industrial Revolution and in 2005. Source: IPCC, 2007a.

GHG gas	Concentration before the Industrial Revolution	Concentration in 2005
CO_2	280 ppm	379 ppm
CH_4	715 ppb	1774 ppb
N_2O	270 ppb	319 ppb

Table 1-2. Emission of greenhouse gases by economic sector, million metric tons CO_2e. Source: EPA, 2013a.

Chapter/IPCC Sector	1990	2005	2007	2008	2009	2010	2011	2011 (%)
Energy	5,267.3	6,251.6	6,266.9	6,096.2	5,699.2	5,889.1	5,745.7	85.7
Industrial Processes	316.1	330.8	347.2	318.7	265.3	303.4	326.5	4.9
Solvent and Other Product Use	4.4	4.4	4.4	4.4	4.4	4.4	4.4	0.1
Agriculture	413.9	446.2	470.9	463.6	459.2	462.3	461.5	6.9
Land-Use Change and Forestry	13.7	25.4	37.3	27.2	20.4	19.7	36.6	0.5
Waste	167.8	136.9	136.5	138.6	138.1	131.4	127.7	1.9
Total Emissions	6,183.3	7,195.3	7,263.2	7,048.8	6,586.6	6,810.3	6,702.3	
Land-Use Change and Forestry (Sinks)	-794.5	-997.8	-929.2	-902.6	-882.6	-888.8	-905.0	
Net Emissions (Emissions and Sinks)	5,388.7	6,197.4	6,334.0	6,146.2	5,704.0	5,921.5	5,797.3	

Table 1-3. Emissions of GHG Agriculture in the USA (Tg CO_2e $year^{-1}$), 1990 to 2011. Source: EPA, 2013a.

Gas/Source	1990	2005	2007	2008	2009	2010	2011	2011 (% of total)
CH_4	171.5	191.5	200.5	200.3	198.6	199.9	196.3	
Enteric Fermentation	132.7	137	141.8	141.4	140.6	139.3	137.4	29.8
Manure Management	31.5	47.6	52.4	51.5	50.5	51.8	52	11.3
Rice Cultivation	7.1	6.8	6.2	7.2	7.3	8.6	6.6	1.4
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.0
N_2O	242.3	254.7	270.4	263.3	260.6	262.4	265.2	
Agricultural Soil Management	227.9	237.5	252.3	245.4	242.8	244.5	247.2	53.6
Manure Management	14.4	17.1	18	17.8	17.7	17.8	18	3.9
Field Burning of Agricultural	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Total	413.9	446.2	470.9	463.6	459.2	462.3	461.5	

Table 1-4. Herd information from Buck Island Ranch (BIR), period 1998 to 2008.

Year	Cows	Pregnant Cows	Bulls	Calves	Average weight of calves (kg)
1998	2933	2410	250	2228	197.8
1999	2865	2036	250	1814	212.7
2000	3106	2312	250	2099	225.0
2001	3213	2640	250	2361	208.2
2002	3205	2666	250	2418	212.3
2003	3114	2596	250	2375	199.6
2004	3014	2043	250	1910	223.2
2005	3209	2337	250	2288	203.7
2006	3215	2625	250	2458	217.3
2007	3306	2838	250	2643	215.5
2008	3414	2687	250	2481	194.6

Table 1-5. Area burned (ha) on Buck Island Ranch (BIR), period between 1998 and 2008.

	Area (ha)	
month, year	Improved	Native
January, 2002	911.5	0.0
February, 2002	20.2	530.3
January, 2003	461.7	607.6
February, 2003	210.5	0.0
January, 2004	115.5	251.1
February, 2004	418.0	414.7
December, 2004	0.0	146.5
January, 2005	481.2	384.2
February, 2005	0.00	104.0
January, 2006	1159.8	1476.5
April, 2006	0.00	342.4

Table 1-6. Average above ground biomass available for burning in Buck Island Ranch (BIR), average from period 1998 to 2008.

	Average biomass (ton ha^{-1})	
Month	Improved	Non-improved
January	3.4	0.4
February	4.6	4.8
April	2.0	1.7
December	5.4	4.0

Table 1-7. Lime, fertilizer, molasses, feed concentrate and fuel used at Buck Island Ranch (BIR), 1998 to 2008.

Year	Lime (ton year^{-1})	Synthetic fertilizer (ton N year^{-1})	Molasses (ton year^{-1})	Diesel (gallons year^{-1}) for molasses transportation	Gasoline (gallons year^{-1})	Diesel (gallons year^{-1})	Feed concentrate (t)
1998	0.0	105.4	468.7	1245.3	4624.4	13021.1	25.0
1999	0.0	68.3	417.7	1109.9	3136.6	13312.4	144.5
2000	0.0	47.6	564.9	1500.9	3208.0	23339.0	166.3
2001	1154.0	42.6	758.7	2015.9	4041.4	17729.2	384.6
2002	1354.0	45.7	524.4	1393.5	4628.6	15156.5	136.9
2003	1802.0	22.6	874.9	2324.6	5578.5	13068.5	243.6
2004	2392.0	94.1	631.3	1677.4	5680.3	12140.0	241.7
2005	524.0	12.5	885.4	2352.4	3332.9	13844.0	511.5
2006	1624.0	0.0	286.7	761.7	3555.6	14175.4	598.0
2007	0.0	0.0	793.9	2109.5	3732.3	17991.5	812.0
2008	0.0	0.0	723.6	1922.6	3566.8	11743.5	272.6

Table 1-8. Source categories and GHG emitted in the production system at in Buck Island Ranch (BIR), 1998 to 2008.

Category	GHG	Methodology
Enteric fermentation (cows)	CH_4	IPCC (2006),Tier 2
Enteric fermentation (bulls)	CH_4	IPCC (2006),Tier 1
Animal waste	CH_4, N_2O	IPCC (2006),Tier 1
Urea for NNP	N_2O	IPCC (2006),Tier 1
Pasture fertilization	N_2O	IPCC (2006),Tier 1
Pasture lime	CO_2	IPCC (2006),Tier 1
Production, transportation, storage and transfer	CO_2	Lal (2004)
Burning of pasture	CH_4, CO, N_2O, NO_x	IPCC (2006),Tier 1
Diesel	CO_2, CH_4, N_2O	EPA (2005)
Gasoline	CO_2, CH_4, N_2O	EPA (2005)

Table 1-9. Global Warming Potential (GWP) of GHG.

GHG	GWP	Source
CO_2	1	IPCC (2007b)
CH_4	25	IPCC (2007b)
N_2O	298	IPCC (2007b)
CO	1.9	IPCC (2007b)

Table 1-10. Data and emissions factor values, units and sources.

Enteric fermentation			
Factor	Value	Unit	Source
DE	62.6	% of GE	EPA (2013b)
Cfi cows	0.322	MJ day^{-1} kg^{-1}	IPCC (2006)
Cfi lactating cows	0.386	MJ day^{-1} kg^{-1}	IPCC (2006)
Ca	0.17	dimensionless	IPCC (2006)
$C_{pregnancy}$	0.1	dimensionless	IPCC (2006)
Ym	6.5	% of GE	EPA (2013b)
EF1	53	(kg CH_4) $head^{-1}$ $year^{-1}$	IPCC (2006)
Milk yield	6.4; 6.7; 5.6; 5.5; 4.4; 4.0; 3.1	(kg of milk) day^{-1}	Minick et al. (2001), average
Milk fat	3.7	%	Marston et al. (1992), average

Manure (CH_4)			
Factor	Value	Unit	Source
$VS_{(T)}$ bulls	1721	(kg dry matter) $animal^{-1}$ $year^{-1}$	EPA (2013b)
$VS_{(T)}$ calves	7.7	(kg dry matter) $(1000\ kg)^{-1}$ day^{-1}	EPA (2013b)
$Bo_{(T)}$	0.17	(m^3 CH_4) (kg of VS excreted)$^{-1}$	EPA (2013b)
$MCF_{S,k}$	1.5	%	IPCC (2006)

Manure (N_2O)			
Factor	Value	Unit	Source
$EF_{3\ PRP}$	0.02	kg N_2O-N (kg N input)$^{-1}$	IPCC (2006)
E_N cows	0.33	kg N day^{-1} $(1000\ kg)^{-1}$	EPA (2013b)
E_N bull	0.31	kg N day^{-1} $(1000\ kg)^{-1}$	EPA (2013b)
E_N calves	0.30	kg N day^{-1} $(1000\ kg)^{-1}$	EPA (2013b)
$Frac_{GASM}$	0.20	kg N vol. (kg of N added)$^{-1}$	IPCC (2006)
EF_4	0.01	kg N_2O–N (kg NH_3-N + NO_x-N)$^{-1}$ vol.	IPCC (2006)
$Frac_{LEACH-(H)}$	0.30	kg N leach. and run (kg on N added)$^{-1}$	IPCC (2006)
EF_5	0.0075	kg N_2O–N (kg N leached and runoff)$^{-1}$	IPCC (2006)

Table 1-11. Data and emissions factor values, units and sources (continuation).

Pasture burning			
Factor	Value	Unit	Source
C_f	0.74	dimensionless	IPCC (2006)
$G_{ef}\,N_2O$	0.21	g (kg dry matter burnt)$^{-1}$	IPCC (2006)
$G_{ef}\,CH_4$	2.3	g (kg dry matter burnt)$^{-1}$	IPCC (2006)
$G_{ef}\,CO$	65.0	g (kg dry matter burnt)$^{-1}$	IPCC (2006)
Synthetic N fertilizer			
Factor	Value	Unit	Source
EF_1	0.01	kg N_2O-N (kg N input) $^{-1}$	IPCC (2006)
F_{SN}	Table 1-7	kg N year^{-1}	BIR[a]
$Frac_{GASF}$	0.1	(kg N volatilized) (kg N applied)$^{-1}$	IPCC (2006)
EF_4	0.01	kg N_2O–N (kg NH_3-N + NO_x-N)$^{-1}$ vol.	IPCC (2006)
$Frac_{LEACH-(H)}$	0.30	kg N leach. and run (kg on N added)$^{-1}$	IPCC (2006)
EF_5	0.0075	kg N_2O–N (kg N leached and runoff)$^{-1}$	IPCC (2006)
Dolomitic lime			
Factor	Value	Unit	Source
$M_{dolomite}$	Table 1-7	kg lime year^{-1}	BIR[a]
$EF_{dolomite}$	0.064	tons of CO_2 (ton of dolomitic lime)$^{-1}$	EPA (2013a)
Production, Transportation, Storage and Transfer			
Factor	Value	Unit	Source
F_{SN}	Table 1-7	kg N year^{-1}	BIR[a]
$M_{dolomite}$	Table 1-7	kg lime year^{-1}	BIR[a]
Equivalent Carbon Emission, N sythetic fertilizer	1.3	kg CE kg $^{-1}$	Lal (2004)
Equivalent Carbon Emission, lime	0.16	kg CE kg $^{-1}$	Lal (2004)
Fuel			
Factor	Value	Unit	Source
Fuel Gasoline	Table 1-7	gallons	BIR[a]
Fuel Diesel	Table 1-7	gallons	BIR[a]
E_{fuel} Gasoline	8.8	kg gallon^{-1}	EPA (2005)
E_{fuel} Diesel	10.1	kg gallon^{-1}	EPA (2005)

[a] BIR: Buck Island Ranch data

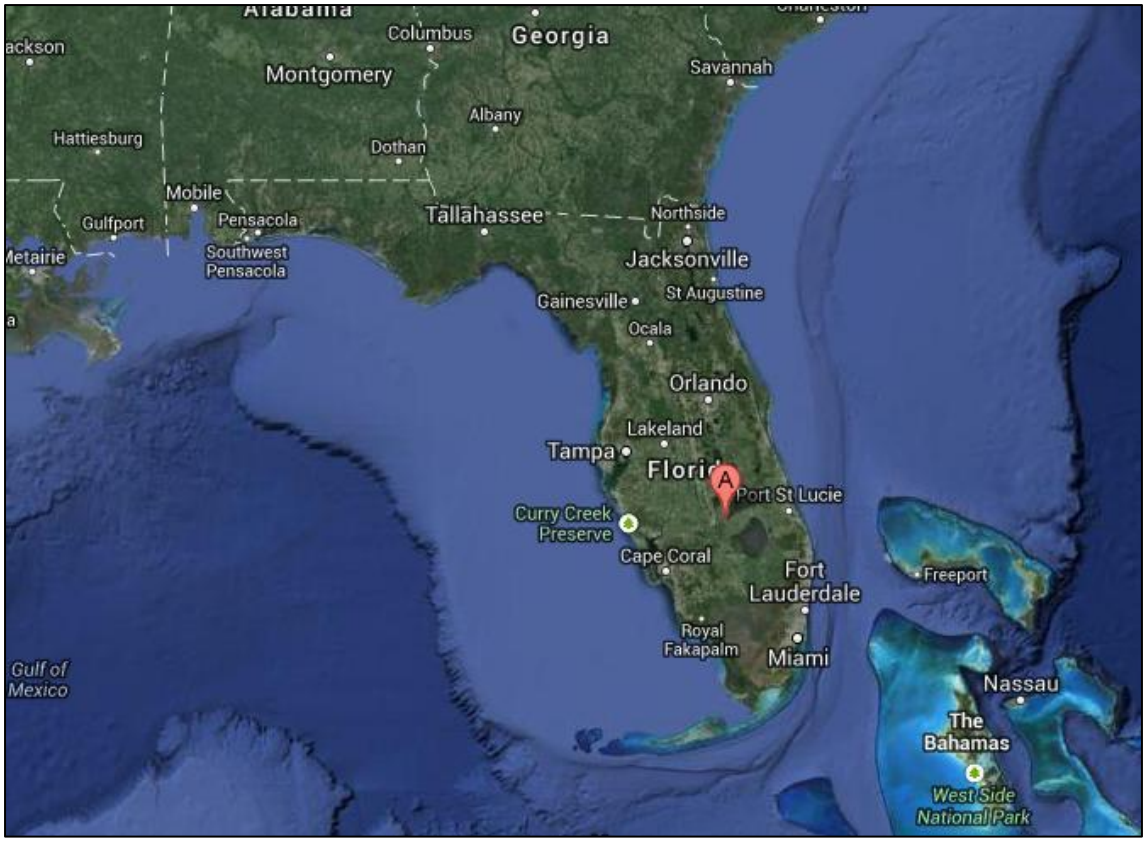
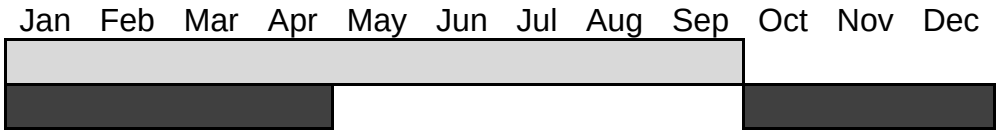


Figure 1-1. Map of the state of Florida. "A" refers to the location of Buck Island Ranch (BIR).



Pregnant
Lactating

Figure 1-2. Calendar of animals' reproductive stage.

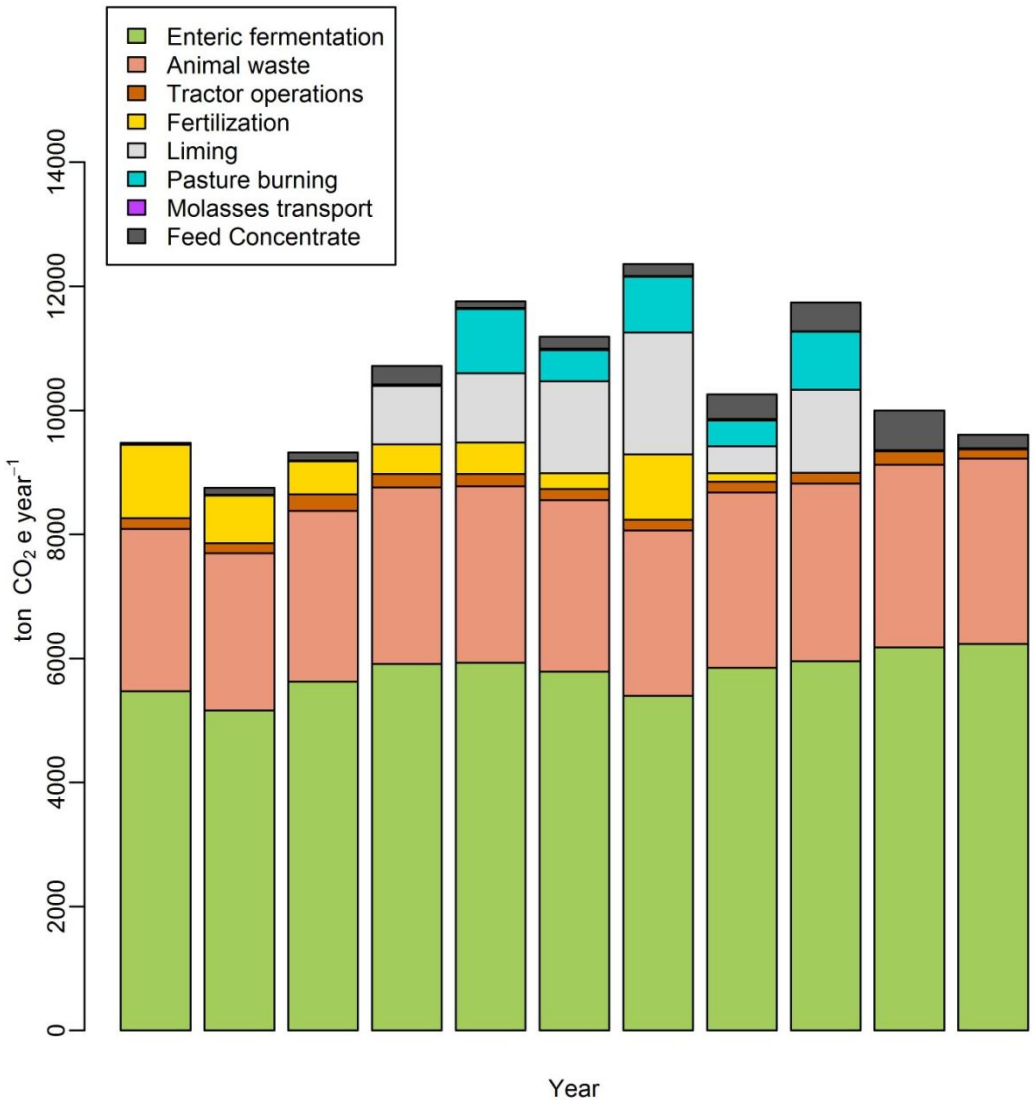


Figure 1-3. Emissions from BIR, ton CO_2e $year^{-1}$.

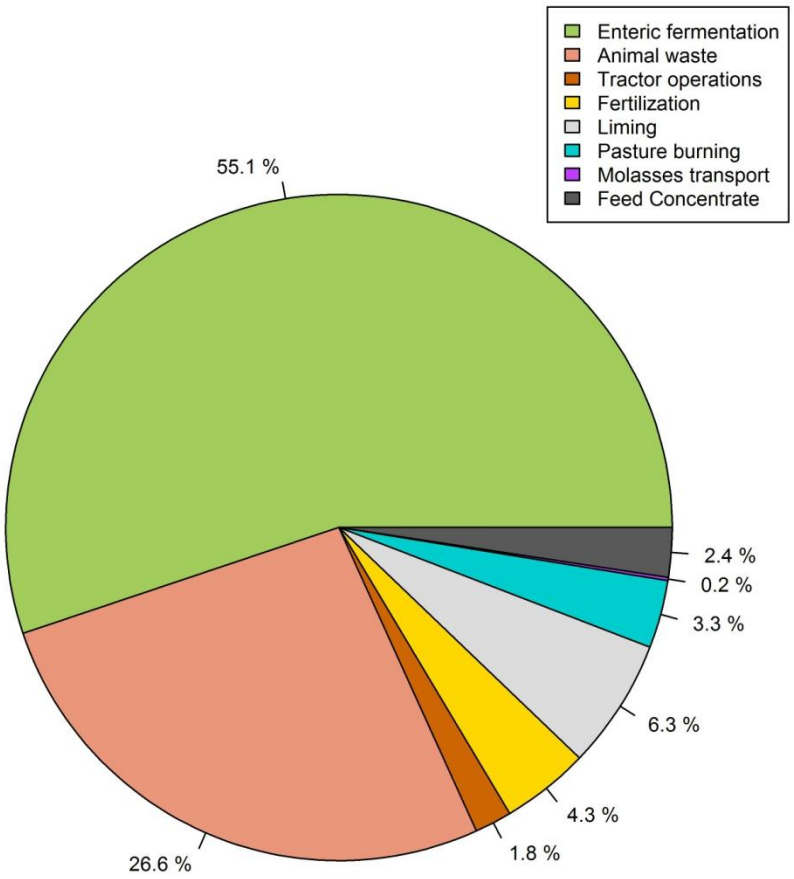


Figure 1-4. GHG emissions from BIR per category, % over average of all years, 1998 to 2008.

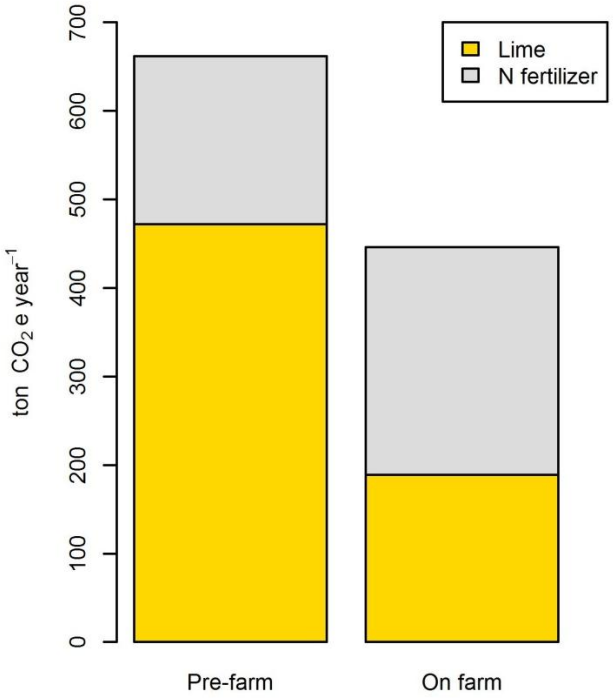


Figure 1-5. Average GHG emissions from synthetic N fertilizer and lime before and after they are applied on the farm.

CHAPTER 2
SENSITIVITY ANALYSIS OF ENTERIC FERMENTATION EMISSION MODEL

Literature Review

A mathematical portrayal of a system is named a model and is usually composed of inputs and outputs (Jones and Luyten, 1998), where one or more equations are used to describe a system's behavior (France and Thornley, 1984). Inputs include constants, fixed values throughout all model runs, and parameters, values that change each time the model runs (France and Thornley, 1984). Outputs refer to time-dependent values that express the status of the system under evaluation (Jones and Luyten, 1998).

Models differ from each other according to the process used for their creation and according to the purpose for which they were built. Empirical models fit mathematical equations to data through statistical methods, while mechanistic or analytical models have their equations built based on biological systems concepts (Keen and Spain, 1992), although empirical knowledge is also used to build mechanistic models to some extent (France and Thornley, 1984). The assumptions used for building mechanistic models establish some restraints that result in their inferior ability to fit results to data sets when compared to empirical models (France and Thornley, 1984). Models can also be classified according to their target use. Models used as decision-making tools are called engineering or functional models, while those focused on explaining physiological and environmental relationships are named scientific or mechanistic (Passioura, 1996). Models can be extremely useful when estimating GHG production on a large scale (Storm et al., 2012), but it should be considered that the use of models along with experiments is crucial when studying different alternatives of a system (Tittonell et al., 2012).

Regarding CH_4 enteric fermentation, several models have been reported in the literature. These models either relate CH_4 emissions to the rumen's biochemistry (mechanistic) or to nutrients consumed by the animals (empirical) (Kebreab et al., 2008). Moe and Tyrrell (1979), for example, developed equations that relate dry matter intake (DMI) to CH_4 emissions at low intake levels and DMI and carbohydrate type at high intake levels for dairy cattle. Another mechanistic model was developed by Dijkstra et al. (1992) following a Michaelis-Menten mass flux dynamic that considers microbial dynamics in the rumen including volatile fatty acids (VFA) absorption depending on rumen VFA. However, EPA and similar organizations in other countries use the model presented by IPCC (2006) to develop inventories of GHG on national levels (Nijdam et al., 2012). Kebreab et al. (2008) evaluated several models and their ability to predict CH_4 output by both dairy and beef cattle. The authors concluded that the IPCC (2006) model's estimated CH_4 agreed fairly well with measured CH_4 values, although it was not the most accurate of the models evaluated. However, authors also emphasize that the national GHG emission inventories level, the difficulty of using mechanistic models might prevent their use.

Sensitivity analysis is performed to assess how uncertainty in a model's input will affect its output and is an important mechanism for analysis of model behavior. Sensitivity analysis is also useful in the process of building a model, since it provides information regarding the importance or irrelevance of considering a parameter in the simulation. This procedure helps identify interactions between inputs and parameters as well as irrelevant inputs (Saltelli et al., 2004; Monod et al., 2006) and, particularly when using global sensitivity analysis, to determine the inputs that should be most accurately measured (Monod et al., 2006). Therefore, performing a sensitivity

analysis of a model is an important tool in determining the reliability of model's outputs (Cukier, 1973).

Sensitivity analysis methods can be separated into two groups: local and global. Local sensitivity analysis evaluates the importance of parameters or variables in a model by performing derivative calculations of the output in relation to these factors, separated in small intervals not related to their uncertainty. The result is a measurement of how intensely the output varies around inputs (Monod et al., 2006). Global sensitivity analysis allows the evaluation of different parameters at the same time and is variance- based, meaning that the factors under evaluation are varied within the limits of their uncertainty (Monod et al., 2006). Results are averaged over the variation of all inputs (Saltelli et al., 1999). Several sensitivity analysis techniques exist, differing in their sampling approaches and evaluation. A description of three of these techniques used in this study follows below.

The Bauer and Hamby (1991) sensitivity analysis creates qualitative indexes to evaluate relative sensitivity of a model's output to its parameter's uncertainty by running the model with a parameter's maximum and minimum value while keeping the remaining parameters at their nominal values, one at a time. This technique is more likely to be successful when used with medium linear models, since it does not identify non-linear or extreme interactions in small models, therefore under-estimating sensitivity indexes. In large, complex models it may take too much computing time to be processed (Monod et al., 2006).

Morris is a model independent sensitivity analysis method, meaning that its use is independent from previous assumptions of input effects on the output and that it can be used in non-linear, non-monotonic models (Saltelli et al., 2004). Monotonicity is a property occurring when a factor has the same signal effect in the

output (Campolongo et al., 2007). This analysis originally aimed at defining which inputs have negligible, additive and linear, or nonlinear or interactive effects in the output, named elementary effects. For this, a computational experimental design is built where inputs are randomly varied in a one-at-a-time fashion so that output variations due to each input are individually evaluated (Morris, 1991). The Morris sensitivity analysis is interpreted based on the indexes μ^* (or μ) and σ, which are the mean and the standard deviation of the elementary effects' distribution (Saltelli et al., 2004) representing the inputs' influence on the output and its interaction and non-linear effects, respectively (Campolongo et al., 2007). Campolongo et al. (2007) proposed a new sampling strategy to better explore the inputs' domain with no extra model simulation where, after a random starting point for the inputs' values, one factor at a time is varied in a random order. The same authors also indicate the use of absolute values for the estimation of μ and σ to avoid the cancellation of effects when the model in non-monotonic, i. e., when an input may vary the signal of its elementary effect on the output.

In the *Fourier Amplitude Sensitivity Test* (FAST), parameters under evaluation are altered simultaneously in a determined frequency within their probability distribution and the model's outputs are Fourier analyzed. This analysis is useful in detecting unimportant parameters, helping to eliminate unnecessary equations in complex models and, due to the combination of parameters' extreme values, it often exposes interactions between parameters. Results of this analysis represent an average of outputs over parameters' uncertainties (Cukier, 1973; Cukier et al., 1978), where the output variance is broken down into partial variances conferred by each parameter and the ratios of these partial variances are used to determine parameters' part in the model output's uncertainty (Xu and Gertner, 2011). This

technique needs less computer runs than those that vary one parameter at a time (Cukier, 1973; Cukier et al., 1975) and can be used in a wide range of equation numbers, types and systems (Cukier, 1973), including nonlinear and non-monotonic models (Xu and Gertner, 2011).

Materials and Methods

Model

The model evaluated was the one presented in 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) for Tier 2 level calculations. This model requires more information than the Tier 1 approach which uses default emission factors and its results are more properly sensitive to changes in animal production systems (Lassey, 2007). The sensitivity analysis was performed regarding three parameters in the IPCC (2006) enteric fermentation CH_4 production model considering animals on pasture or in feedlots. Although the case study was performed using an example of adult animals, the parameters related to pregnancy and lactation did not offer a large range of variation. Therefore, the SA was performed regarding growing animals to also consider weight gain. Net energy for work refers to energy spent by animals performing activities such as pulling plows, etc., and since such activities are not performed by the animals in Florida it was also considered zero. Remaining parameters (not under evaluation) were used at their default values as presented in the IPCC (2006) (Table 2-1). IPCC's (2006) Tier 2 enteric fermentation equations were transformed into a function in R using the *function()* command in order to perform the sensitivity analysis.

$$GE=[(\frac{\mathrm{NEm+NEa+NEl+NEwork+NEp}}{\mathrm{REM}}) +(\frac{\mathrm{NEg}}{\mathrm{REG}})]/(\frac{DE\%}{100})$$

where

GE= gross energy, MJ day^{-1}

NEm= Net energy required for animal maintenance, MJ day^{-1}

NEa= Net energy for animal activity, MJ day^{-1}

NEl= Net energy for lactation, MJ day^{-1}

NEwork= Net energy for work, MJ day^{-1}

NEp= Net energy required for pregnancy, MJ day^{-1}

REM= ratio of net energy available in a diet for maintenance to digestible consumed

NEg= Net energy needed for growth, MJ day^{-1}

REG= Ratio of net energy available for growth in a diet to digestible energy consumed

DE= digestible energy expressed as a percent of gross energy (percent)

Formulas used to calculate each of the factors involved in GE calculation are as follows:

$$NEm = Cfi \times (weight)^{0.75}$$

where

NEm= Net energy required for the animal for maintenance, MJ day^{-1}

Cfi= coefficient, varies for each animal category, MJ day^{-1} kg^{-1}

Weight= live weight of animal, in kg

$$Weight = iw + (WG \times days)$$

where

iw= initial weight, considered to be 200 kg

WG= average daily weight gain of the animals in the population, kg day^{-1}

days= days since the beginning of the production cycle

$$NEa = Ca \times NEm$$

where

NEa= Net energy for animal activity, MJ day^{-1}

Ca= activity coefficient corresponding to animal's feeding situation, dimensionless

NEm= Net energy required for the animal for maintenance, MJ day^{-1}

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

where

NEg= net energy needed for growth, MJ day^{-1}

BW= average body weight of the animals in the population, kg

C= coefficient with values of 0.8 for females, 1.0 for castrated animals and 1.2 for bulls. In this case 0.8 was used.

MW= mature live weight of an adult female cow in moderate body condition, kg

ADG= average daily weight gain of the animals in the population, kg day^{-1}

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

where

REM= ratio of net energy available in a diet for maintenance to digestible consumed

DE= digestible energy expressed as a percentage of gross energy

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

where

REG= Ratio of net energy available for growth in a diet to digestible energy consumed

DE= digestible energy expressed as a percentage of gross energy. The value used was the same as in the REM calculation

After that, a daily emission factor for each category was calculated with the formula below.

$$\text{DayEmit} = \left[\frac{GE\ x\ \left(\frac{Ym}{100}\right)}{55.65}\right]$$

where:

DayEmit = emission factor, kg CH_4^{-1} $head^{-1}$ day^{-1}

GE = gross energy intake, MJ day^{-1}

Ym = CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4 (%).

55.65 = a factor for the energy content of CH_4, MJ (kg CH_4) $^{-1}$

To determine yearly emissions for each category, the formula below was used.

$$\text{Emissions} = \text{DayEmit} \times 365$$

where:

Emissions = total emissions in a month for the category, kg CH_4 $year^{-1}$

DayEmit = emission factor for the category, kg CH_4 $head^{-1}$ day^{-1}

365 = days in the year

Data Source

The sensitivity analysis was performed regarding three parameters in the IPCC (2006) ruminal CH_4 production model considering finishing animals on pasture or in feedlots. For this, a literature review was performed in order to obtain the range of possible values for the parameters under evaluation (Table 2-2 and Table 2-3). Since the values differ considerably between the two feeding situations (animals on pasture or on feedlot), sensitivity analyses were made separately. Three global sensitivity analysis methodologies were applied: vary-one-at-a-time (Bauer and Hamby, 1991), Morris (Morris, 1991) and Fourier Amplitude Sensitivity Test (FAST; Cukier, 1973).

The analyses were made using different methods from the R software that will be described below. R is a software built for statistical computation, including linear and non-linear regression models, time series analysis, smoothing, etc., with a flexible graphical environment. R comes with several basic packages, but packages for specific functions can be downloaded (Venables et al., 2011).

Vary-one-at-a-time (OAT)

The OAT method was programmed using the R language (Venables et al., 2011). One parameter was varied at a time in an equally spaced domain as shown in Figure 2-1. Remaining parameters were maintained at their average values. The index of relative sensitivity was calculated by the following:

$$I = [\max y((zi)) - \min y((zi))] / \max y((zi))$$

where

zi= parameter value;

y(zi)= model's output when parameter value is zi.

Morris

For the *Morris* sensitivity analysis, the parameters were sampled 2560 times within the experimental space delimited by the values in Table 2-2 and Table 2-3. This analysis was made using the package sensitivity (Pujol et al., 2013), library "sensitivity", function *morris()*. In this method, an OAT (one at a time) experimental design is developed where

r is the number of elementary effects for each input;

levels refers to the number of levels in the design, i. e., how many times the model runs;

grid.jump is the number of jumps in the experimental grid, usually half the number of levels;

scale is true if the inputs are scaled to vary between 0 and 1, to avoid misinterpretation when inputs have contrasting orders of magnitude.

In this analysis,

r = 2560;

levels= 2560;

grid.jump= 1280;

scale= T (true).

The development of the experimental design can be observed in Figure 2-2, where we can see an example of how the random variation evolves and covers the domain of the three inputs under evaluation. The experimental design for animals on pasture and feedlot can be observed in fast99(). An important feature of this function is that it runs the extended FAST method, which allows for the consideration of both parameters direct effect in the model's output and its interactions with other factors (Saltelli et al., 1999). In this function the arguments are

model refers to the model under evaluation;

factors are the inputs that will be analyzed regarding their influence in the model's output;

n is the sample size (Cukier et al., 1978);

M is the interference parameter (Cukier et al., 1978), used to decrease the error. Default value of 4 was used (Cukier, 1973);

omega is the frequency used to sample each factor;

q is the distribution of inputs, set as uniform in this analysis;

q.arg refers to the input's intervals, defined in Table 2-2 and Table 2-3;

x is the vector where input values are stored;

y is a vector where the model responses are stored.

FAST returns two values for each parameter evaluated, the main effect of the parameter and the interaction of the parameter with other factors. All of the values summed are equal to 1.

The function returns three values:

μ^*: mean of each input's elementary effects originally described by Morris (1991);

μ: mean of each input's absolute values of elementary effects as proposed by Campolongo et al. (2007);

σ: standard deviation of each input's elementary effects.

FAST

For the FAST sensitivity analysis, the parameters were sampled within the experimental space delimited by the values in Table 2-2 and Table 2-3, shown in Figure 2-6. This analysis was made using the package sensitivity (Pujol et al., 2013), library "sensitivity", function *fast99()*. An important feature of this function is that it runs the extended FAST method, which allows for the consideration of both parameters' direct effect in the model's output and its interactions with other factors (Saltelli et al., 1999). In this function the arguments are

model refers to the model under evaluation;

factors are the inputs that will be analyzed regarding their influence in the model's output;

n is the sample size (Cukier et al., 1978);

M is the interference parameter (Cukier et al., 1978), used to decrease the error. Default value of 4 was used (Cukier, 1973);

omega is the frequency used to sample each factor;

q is the distribution of inputs, set as uniform in this analysis;

q.arg refers to the input's intervals, defined in Table 2-2 and Table 2-3;

x is the vector where input values are stored;

y is a vector where the model responses are stored.

FAST returns two values for each parameter evaluated, the main effect of the parameter and the interaction of the parameter with other factors. All of the values summed are equal to 1.

Results

Results can be observed in Table 2-4 and Figure 2-6 through Figure 2-8. One of the advantages of using the OAT analysis is that, particularly when using graphic resources, one can observe the basic relationship between output and inputs. We can observe in Figure 2-6 that CH_4 production (kg animal^{-1} day^{-1}) increases with the increasing values of CH_4 conversion rate (Ym, %) and ADG (average daily gain, kg animal^{-1} day^{-1}) and decreases with greater values of digestible energy (DE, %). The association between CH_4 emissions (kg animal^{-1} year^{-1}) with digestible energy (DE, %) is negative and slightly quadratic and ADG (kg animal^{-1} day^{-1}) had a quadratic relationship with CH_4 emissions (kg animal^{-1} year^{-1}) (Figure 2-6).

The relationship of CH_4 emissions (kg animal^{-1} year^{-1}) with CH_4 conversion rate (Ym, %) was positive and linear. This factor is used only once in the estimation of CH_4 production, when multiplied by the gross energy (GE, MJ day^{-1}), thus the linear relationship:

$$\text{DayEmit} = \left[\frac{GE\ x\left(\frac{Ym}{100}\right)}{55.65}\right]$$

Observing the OAT indexes obtained for each parameter (Figure 2-6 and Table 2-4) we can see that ADG is the most important parameter influencing the output of the model being evaluated, independent of feeding situation. However, when the model is used to simulate CH_4 emissions of animals on pasture, digestible

energy available for animals influences the output more intensely than CH_4 conversion rate Ym.

Results from the sensitivity analysis performed using the FAST method can be observed in Figure 2-7. One of the important aspects of this analysis is that separates direct effects from a parameter in the output and its interaction with other factors, where the sum of the FAST index should be 1. The ranked importance of parameters in each simulation scenario was not different from the previous analysis, where ADG (kg animal^{-1} day^{-1}) was considered the most import parameter to influence the model's output. When simulation was made for grazing conditions, DE (%) was the second most important factor influencing CH_4 emissions on pasture conditions, similar to what was found in the analysis with OAT and Morris methodologies (Table 2-5). Interactions between parameters and other factors used in the model do not seem to have a major importance in the model's output according to the FAST analysis. However, when we observe the results from the Morris analysis (Figure 2-8) we can see that, according to the σ values, interactions and non-linearity play an important role in the behavior of the model particularly regarding the digestible energy (DE, %) in simulations made for animals on pasture, the CH_4 conversion rate (Ym, %) for simulation of animals on feedlot and, for both feeding situations, average daily gain (ADG, kg animal^{-1} day^{-1}).

Discussion

Energy partitioning of consumed feed in animals follows the scheme below (Figure 2-9), where we can see that consumed gross energy (GE) is lost in feces, urine and CH_4. Total consumed energy minus energy lost in the feces is referred to as digestible energy (DE), and digestible energy minus energy lost in urine and as CH_4 is called metabolizable energy (ME). Remaining energy, also referred to as net

energy (NE), is used by animals for maintenance, growth and production (Minson, 1990; Van Soest, 1982).

The model evaluated by this sensitivity analysis is based on the concepts described above. In the first instance, the GE is calculated for animals based on their energy requirement for maintenance, growth, milk production and reproduction. This calculation is based on production data or production estimates (ADG) associated with feed information, assessed by the model's inputs DE and Ym. In animal feed, DE usually refers to soluble carbohydrates, organic acids and structural carbohydrates that are not coated by lignin layers (Minson, 1990) and is closely related to dry matter digestibility (Moir, 1961) and organic matter digestibility (Rittenhouse et al., 1971). Feces are composed of undigested material, animal's endogenous waste and microbial material (Van Soest, 1982). Methane (CH_4) conversion rate (Ym) is a ratio between CH_4 produced by the animals and feed intake, both in units of energy of combustion. In grazing trials, assessing animal intake may be troublesome and lead to uncertainty in individual Ym estimations, while on a population scale the Ym can have uncertainty from the inter-animal variation (Lassey, 2007). These characteristics may difficult retrieving reliable data of Ym to be used in national scale inventories.

Decreasing the amount of energy used in the production of CH_4 can increase animal's energy-use efficiency and consequently lead to an improvement in economical competence (Beauchemin and Mcginn, 2006; Kurihara et al., 1999). Analyzing data from 20 energy metabolism studies with dairy cattle, Yan et al. (2010) found that energy partitioning, use efficiency, metabolism and animal productivity can have an effect on the proportion of energy spent in CH_4 production.

DE was found to be negatively related to dry matter intake (Nkrumah et al., 2006). Kurihara et al. (1999), evaluating CH_4 production and energy partitioning in Brahman cattle fed two tropical forage and one high grain diets, found that less CH_4 was produced as DE (%) increased. In that experiment, DE ranged from 44 to 59% for the forages and achieved 70% in the high grain diets. A decrease in DE was reported by Beauchemin and Mcginn (2006) when feeding animals unsaturated fat using canola oil and resulted in a reduction in daily CH_4 emissions. In that experiment, however, the reduction in DE (%) occurred along with a reduction in total GE and the authors suggest that the use of fats in animal diet might not be feasible because of their negative effect on total DE intake by the animals.

For grazing beef cattle, EPA calculates the DE values used in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990- 2011 (EPA, 2013a) as a weighted average over a diversity of forages' DE and 5 to 15% supplementation, using a distinct value for the western regions to consider its general lower quality forage. For animals on feedlots, one value of DE was used for the entire country but it was considered to vary annually according to feed type nutritional information and availability (EPA, 2013b). All the sensitivity analysis performed show that in the model assessed. DE is of crucial importance in the output when simulations are made for animals on pasture. Considering the large population of cattle in the U.S. kept on pasture, rangeland and meadow, which reached 49.5 million head in 2011 (EPA, 2013b), gathering precise information on DE of feed will significantly affect GHG estimation of the beef production sector.

Animals fed high concentrate diets may have less energy lost as CH_4 (Beauchemin and Mcginn, 2005;Kurihara et al., 1999). However, changing animal feed from pasture to concentrate should consider the emissions associated with

production of feed at a farm level (Yan et al., 2010). Also, in the context of climate change and its future consequences to agricultural practices and production, ruminant's ability to grow and produce when fed fibrous feed that is unsuitable for human consumption should not be ignored (Beauchemin et al., 2010).

The amount of total energy consumed used in the production of CH_4 can be affected by several factors. Yan et al. (2010) reviewing 20 studies made with dairy cows fed fresh grass and grass silage found that less energy was used in the production of CH_4 when feed intake and energy used in milk production increased. The authors also concluded that CH_4 emissions and milk production are negatively related, i.e., an increase in the value of energy converted into CH_4 was related to a decrease in energy use efficiency.

For simulations made for animals on feedlot CH_4 conversion rate Ym (%) influenced the model's output more strongly than digestible energy. This aspect is of particular importance considering the difference found in Ym from experimental studies and the values used in national scale inventories. Beauchemin and Mcginn (2005), studying CH_4 emissions from cattle fed corn or barley diets, found that Ym from animals on barley feed was greater than the ones indicated by IPCC (2006). A sorghum based high-grain diet fed to cattle by Kurihara et al. (1999), however, presented a Ym similar to the one suggested by IPCC (2006).

For simulations made for animals on pasture it was observed that Ym was of lesser relevance in the use of the model. However, this does not imply Ym is irrelevant when estimating emissions from beef production on pasture. In fact, the extrapolation of Ym values from animal populations to national scale GHG inventories can introduce considering amount of uncertainty to the result (Lassey, 2007). An analysis of the sources of uncertainty in Canadian's livestock model used

for estimating CH_4 emissions from enteric fermentation from non- dairy cattle showed that Ym and the coefficient for calculating net energy for maintenance were the most relevant sources of uncertainty (Karimi-Zindashty et al., 2012). This is valuable information considering the difficulty involved in obtaining these data from field experiments on pasture, to which only the SF_6 technique can currently be used (Lassey, 2007; Storm et al., 2012). Kebreab et al. (2008) evaluated different empirical and mechanistic models developed to estimate CH_4 emissions, including the IPCC (2006) model evaluated in this study. The authors concluded that mechanistic models are better CH_4 predictors, however due to the difficulty related to their use the authors suggest that these models should be used in order to more accurately estimate Ym and its change due to modifications in feed. For simulations made for animals on pasture, the USDA uses a fixed value of 6.5%. For animals on feedlot, the mechanistic model MOLLY as described in Kebreab et al. (2008) is used to estimate Ym. An important aspect of the model evaluation is that (Kebreab et al., 2008) did not evaluate prediction ability for animals maintained on pasture due to lack of reliable information related not only to CH_4 emissions but also to the characteristics that may affect animals in pastoral environments.

An appropriate way to evaluate and compare different production systems is to express CH_4 emissions per unit of animal production (Kurihara et al., 1999), particularly when considering that CH_4 production relates to energy channeled not into production but lost to the environment (Lassey, 2007). In beef production, ADG is an important parameter to evaluate production efficiency. Dividing CH_4 emissions from enteric fermentation by ADG used in the simulation (Figure 2-10) we can see that increases in productivity reduce CH_4 ADG^{-1}, supporting the concept that increases in productivity enhance GHG efficiency. In a study where Brahman cattle

were fed diets varying in digestibility and N content animal weight change was found to have a negative quadratic relationship with CH_4 emissions when these were expressed as g CH_4 (kg live weight gain)$^{-1}$. This implies that reduction in CH_4 may only be achieved in animals that present low weight gains (Kurihara et al., 1999). The IPCC (2006) model for enteric fermentation seems to agree with this concept. According to Figure 2-10, animals on pasture seem to have higher potential to increase their CH_4 use efficiency. In fact, the high Ym found in tropical forages suggests considerable potential to improve animal productivity in the Tropics (Kurihara et al., 1999). This increase in productivity would therefore not only benefit the farmer, but also be beneficial to the environment by reducing GHG emissions per unit of animal product (Lassey, 2013).

Interactions among parameters and other inputs in the model are evaluated by both the FAST and the Morris analysis. The FAST analysis returns one value for the main effect of the parameter on the output and one value for a parameter's interactions with other factors. Similarly, Morris analysis returns two values, one referring to main effects of the parameter in the output (μ) and another to the parameter's interactions and non-linearity (σ). Campolongo et al. (2007) highlight the importance of considering both μ and σ when evaluating the importance of a parameter because μ is slightly disposed to Type II error, i. e., when a parameter is significant but the analysis is unable to detect it.

Looking at the ranking of the parameters evaluated in this sensitivity analysis, we observe that the main effect of parameters on the model's output is the same in the three sensitivity analysis Table 2-5. The interactions of the parameters follow the tendency of their ranking's importance, so that the most important parameters are the ones that show interaction. The FAST analysis shows that interaction plays a

minor role in the use of the model. Therefore, the high values for σ found by the Morris analysis for ADG in both pasture and feedlot simulations and in DE for pasture simulations seem to refer more strongly to the parameter's non- linear relationship with the output in CH4 animal^{-1} year^{-1} also observed in the OAT sensitivity analysis.

Conclusions

Interactions seem to be of minor importance in the use of this model. The most important parameter influencing the output in the enteric fermentation model evaluated is ADG (kg animal^{-1} day^{-1}) for simulations made for animals on both pasture and feedlot. The implication for this is that more accurate values of ADG should greatly influence the results found with the model. Considering its generalized use on large-scale modeling such as national GHG inventories, it may be of importance to more precisely acquire information on ADG to improve the use of the model.

The second most important factor influencing the model's output for simulations on pasture is DE (%) followed by Ym (%). For simulations made for animals on feedlot, Ym (%) is the second most important parameter influencing the model's output followed by DE (%). Data on both these parameters present considerable difficulty to be measured on experimental basis and include the need for expensive equipment and trained personnel. However, if one aims at improving the use of models, more research is necessary to collect reliable information on these parameters.

Table 2-1. Default values for parameters not evaluated in sensitivity analysis.

Parameter	Description	Feedlot	Pasture	Unit	Source
MW	mature body weight of an adult female in moderate body condition	450	450	kg	IPCC (2006)
C	coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls	0.8	0.8	dimensionless	IPCC (2006)
Cfi	coefficient varying for each animal category	0.322	0.322	MJ d^{-1} kg^{-1}	IPCC (2006)
Ca	activity coefficient corresponding to animal's feeding situation	0	0.17	dimensionless	IPCC (2006)

Table 2-2. Digestible energy (DE, %) and methane conversion rate (Ym, %) values and sources used in the sensitivity analyses.

	Feeding conditions		
Parameters	Grazing	Feedlot	Source
DE	55- 75	75-85	IPCC (2006)
Ym	5.5- 7.5	2-4	IPCC (2006)

Table 2-3. Average daily gain (ADG, kg/day) values and sources used in the sensitivity analyses.

ADG	Diet composition	Source
0.06- 0.70	Limpograss	Sollenberger et al. (1997)
0.28- 0.34	Limpograss	Stewart Jr. et al., (2007)
0.30- 0.48	Bermudagrass	Mislevy and Dunavin (1993)
0.43- 0.62	Florico Stargrass	
0.37- 0.49	Florona Stargrass	
0.31- 0.33	Pensacola Bahiagrass	
0.19- 0.24	Tifton 9	
0.25- 0.56	Floralta Limpograss	Sollenberger et al. (1989)
0.17- 0.56	Pensacola Bahiagrass	
0.49- 1.14	4.5% molasses 3.5% cottonseed meal 0.75% limestone 82.5% ground corn 8% ground alfalfa hay 0.75% urea	Phillips et al. (2006)

Table 2-4. OAT, FAST and Morris indexes for the enteric fermentation emission model (IPCC, 2006). ADG = average daily gain, kg animal^{-1} day^{-1}; DE = digestible energy, %; Ym = methane conversion rate, %.

Parameter	OAT			
	Main Effect		Interactions	
	Pasture	Feedlot	Pasture	Feedlot
Ym	0.27	0.5	-	-
DE	0.41	0.16	-	-
ADG	0.58	0.68	-	-
Parameter	FAST			
	Main Effect		Interactions	
Ym	0.08	0.46	0.01	0.02
DE	0.25	0.03	0.03	0.00
ADG	0.64	0.48	0.03	0.02
Parameter	Morris			
	Main Effect (μ)		Interactions and non-monotonicity (σ)	
Ym	14.4	15.5	4.2	3.1
DE	-24.2	-4.1	8.8	1.2
ADG	39.8	15.8	8.7	3.2

Table 2-5. Ranking of parameters' influence in the output of IPCC's (2006) enteric fermentation model.

	Pasture			Feedlot		
	OAT	FAST	Morris	OAT	FAST	Morris
Ym	3	3	3	2	2	2
DE	2	2	2	3	3	3
ADG	1	1	1	1	1	1

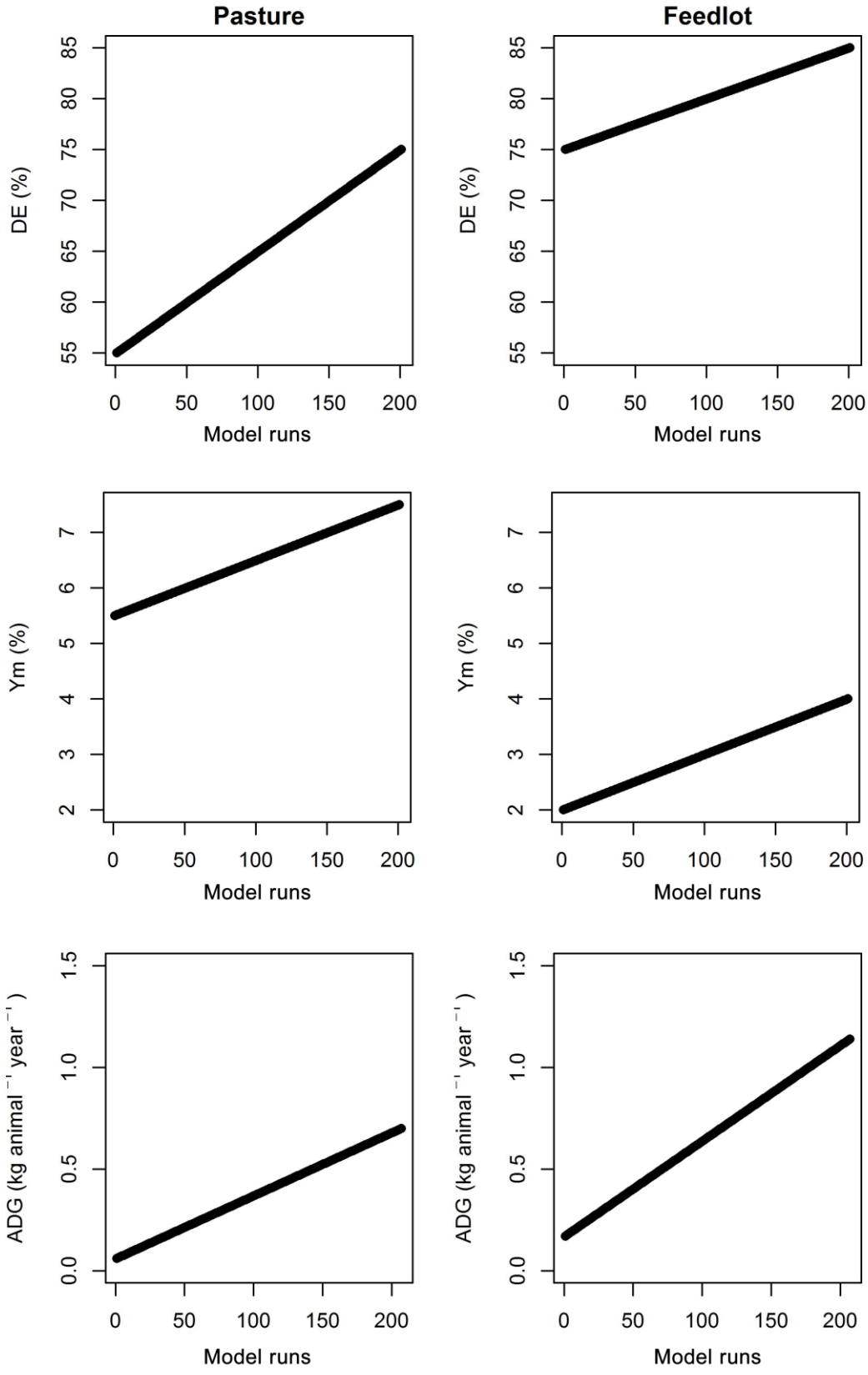


Figure 2-1. OAT experimental design used in the sensitivity analysis.

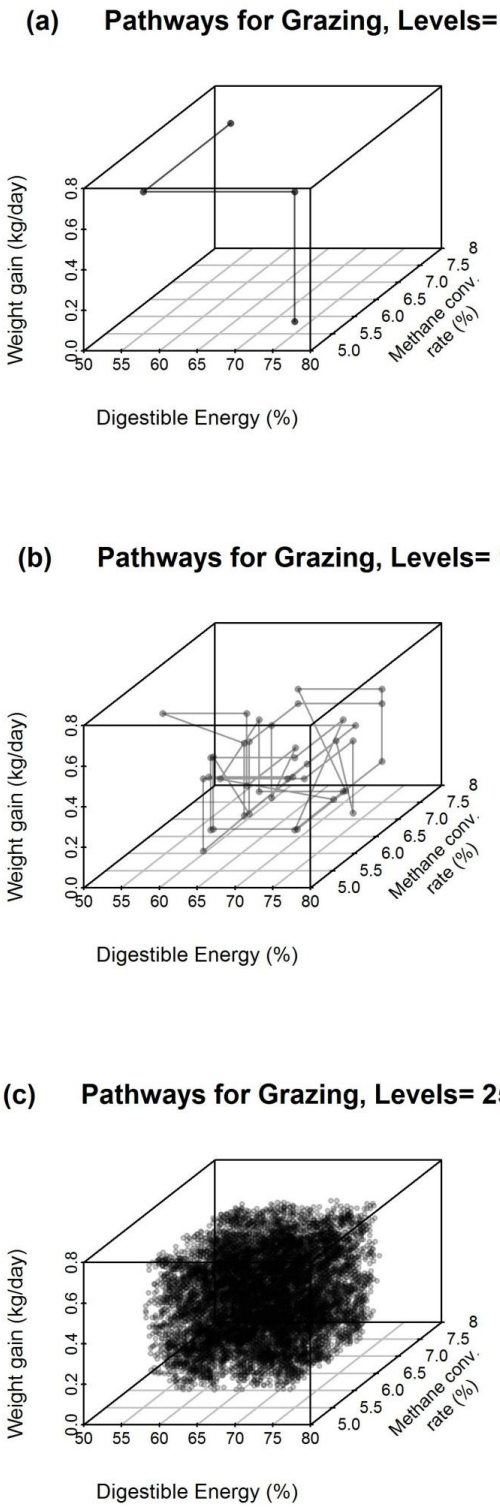


Figure 2-2. Evolution of the experimental design in Morris sensitivity analysis (a through c) for the parameters' intervals in the pasture's evaluation.

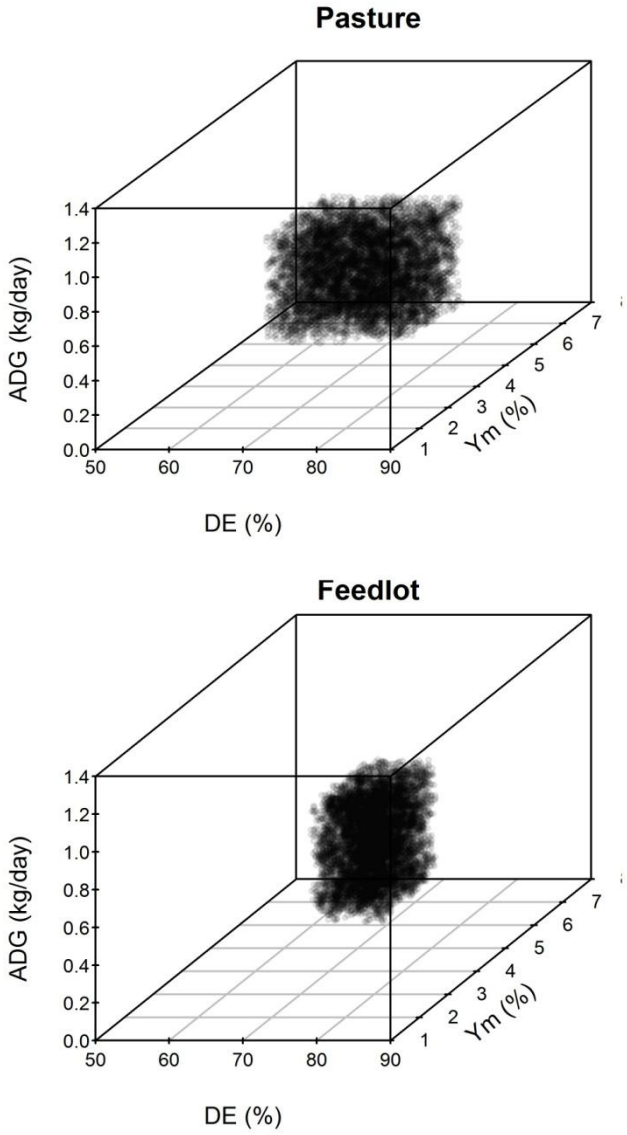


Figure 2-3. Experimental design in the FAST method for animals on pasture and on feedlot. ADG= average daily gain, kg animal^{-1} day^{-1}; DE= digestible energy, %; Ym= methane conversion rate, %.

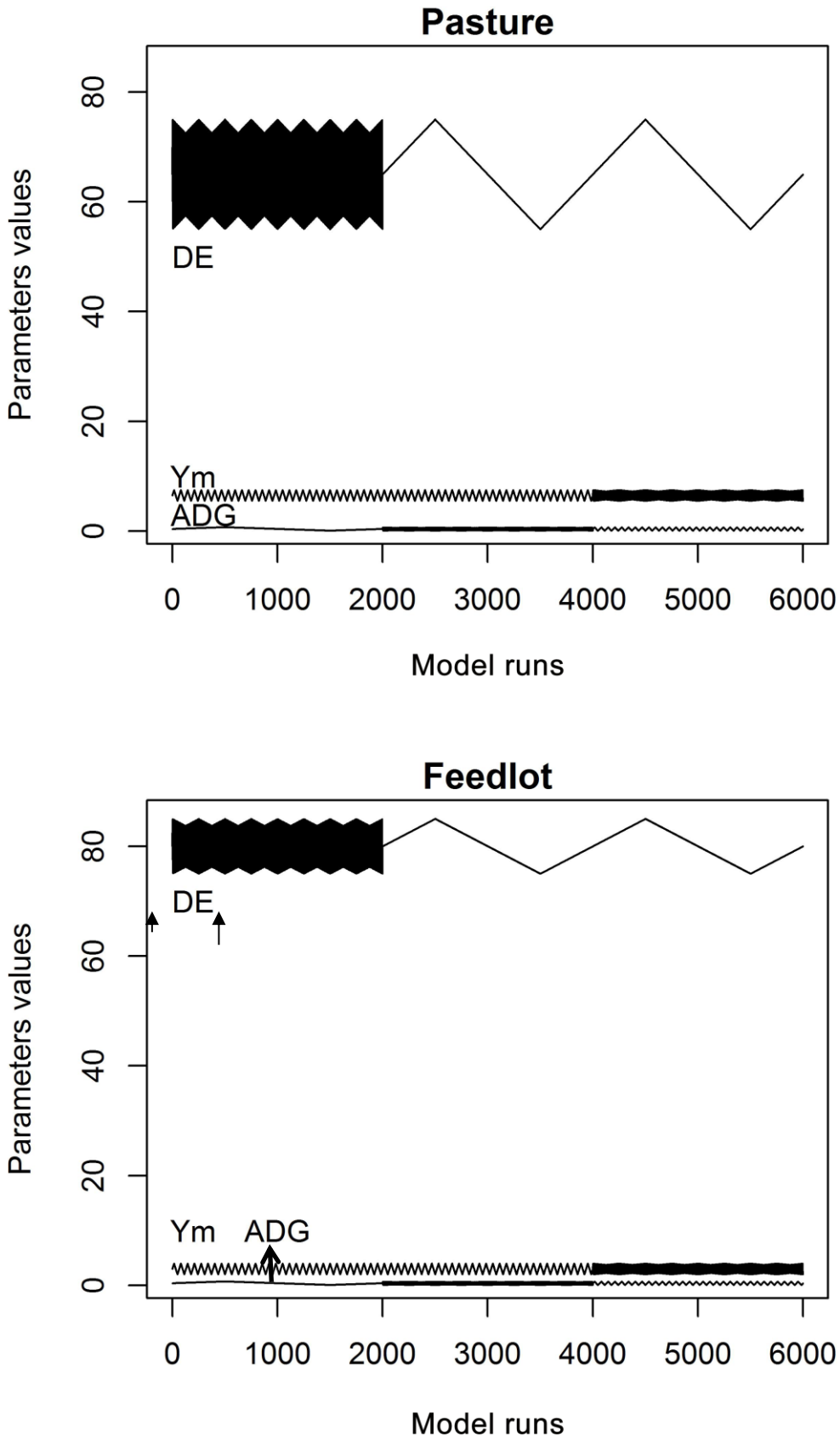


Figure 2-4. Experimental design in the FAST sensitivity analysis. ADG = average daily gain, kg animal^{-1} day^{-1}; DE = digestible energy, %; Ym = methane conversion rate, %.

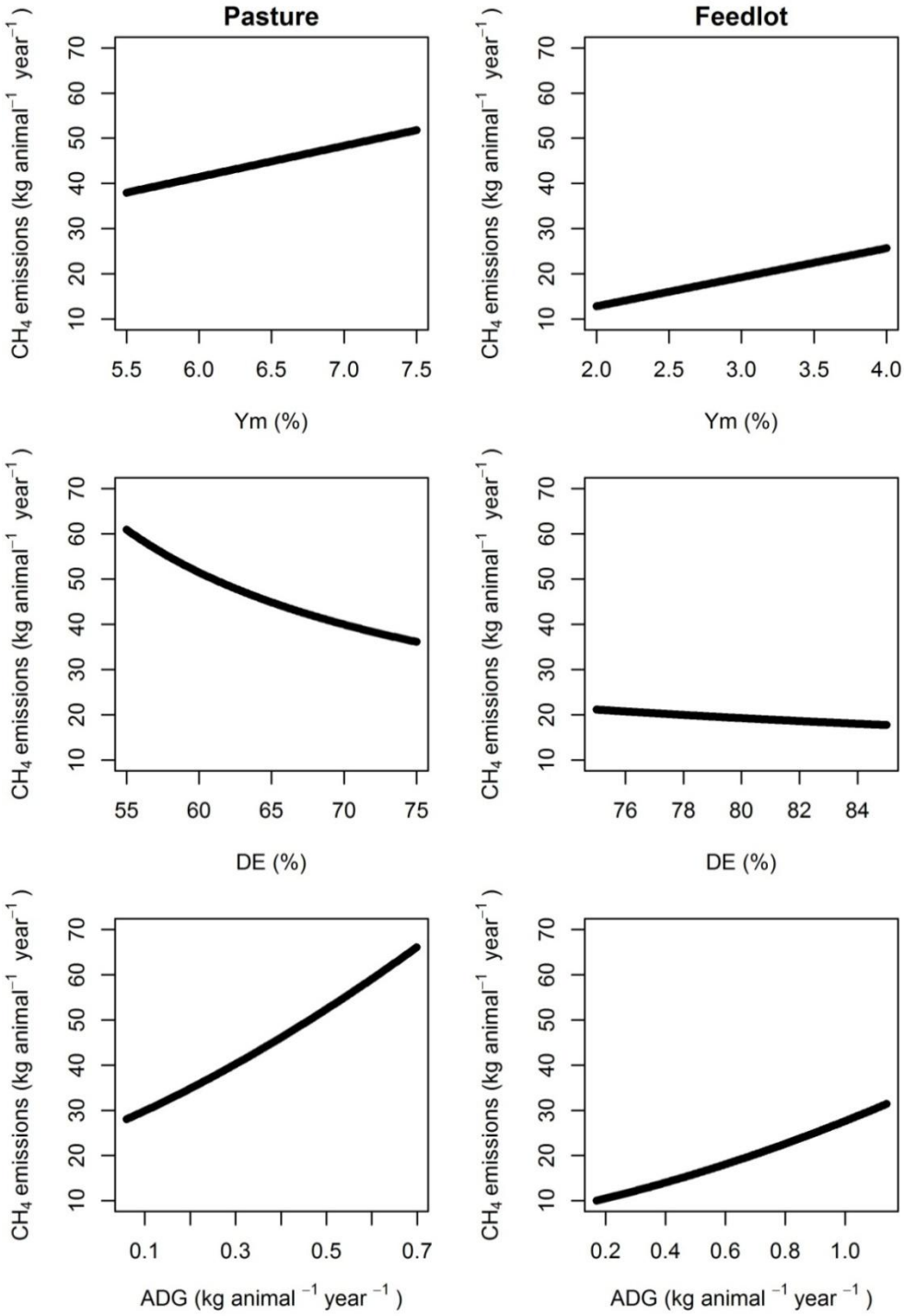


Figure 2-5. Output of enteric fermentation methane emission model (IPCC, 2006) in kg CH_4 animal^{-1} year^{-1} as a function of parameter values in the OAT sensitivity analysis method.

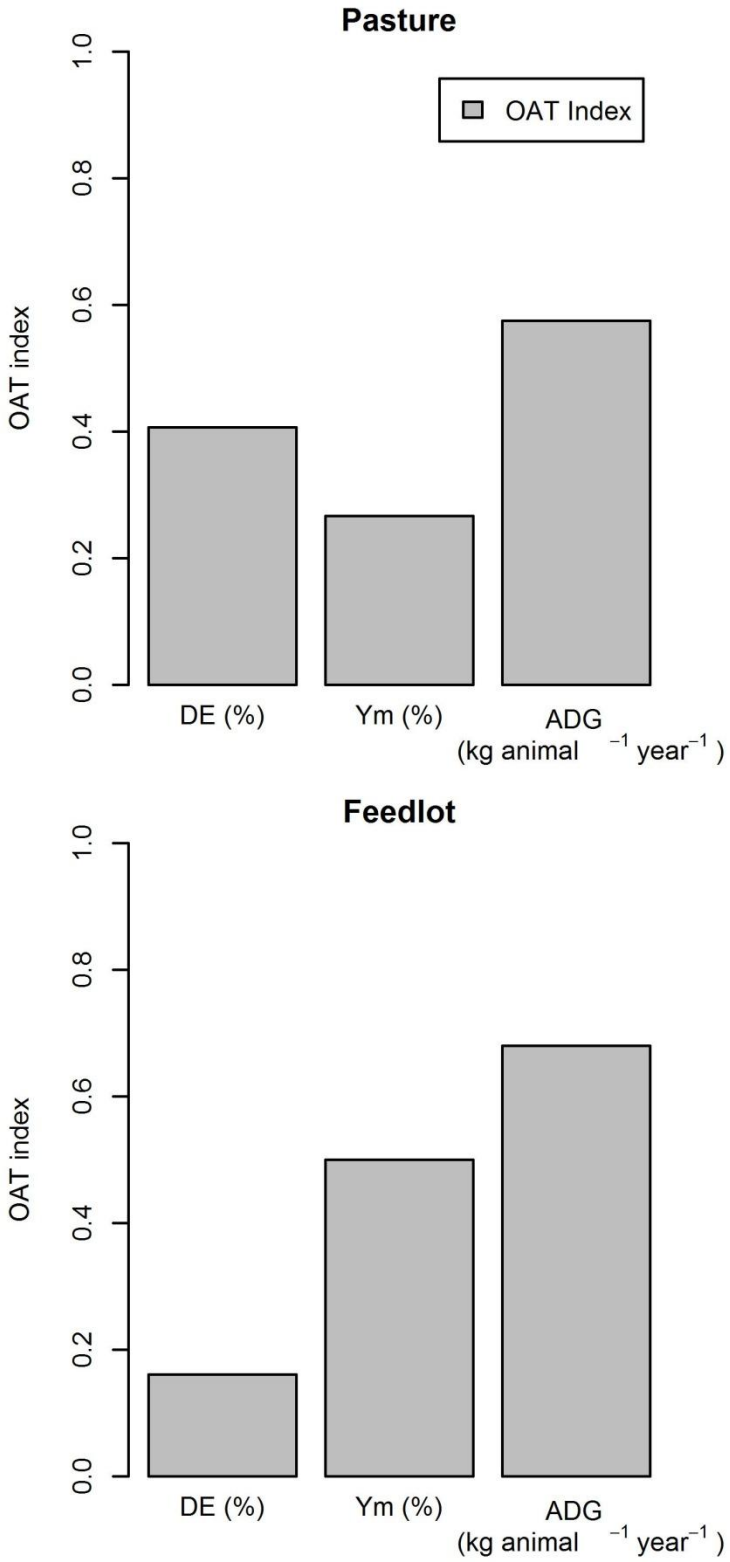


Figure 2-6. OAT index for sensitivity analysis of simulations on pasture and feedlot situations.

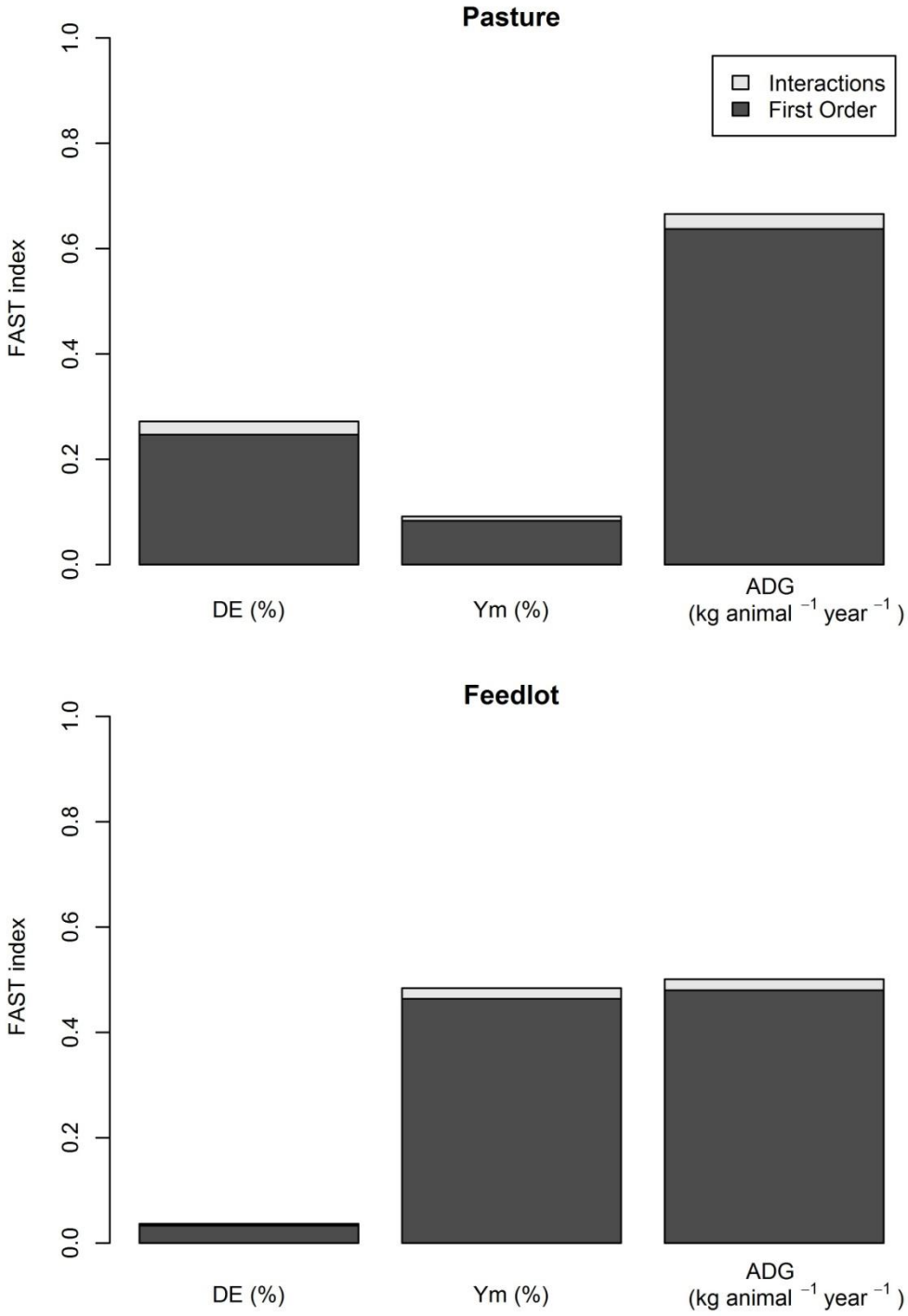


Figure 2-7. FAST indexes for the enteric fermentation emission model (IPCC, 2006). ADG = average daily gain, kg animal^{-1} day^{-1}; DE = digestible energy, %; Ym = methane conversion rate, %.

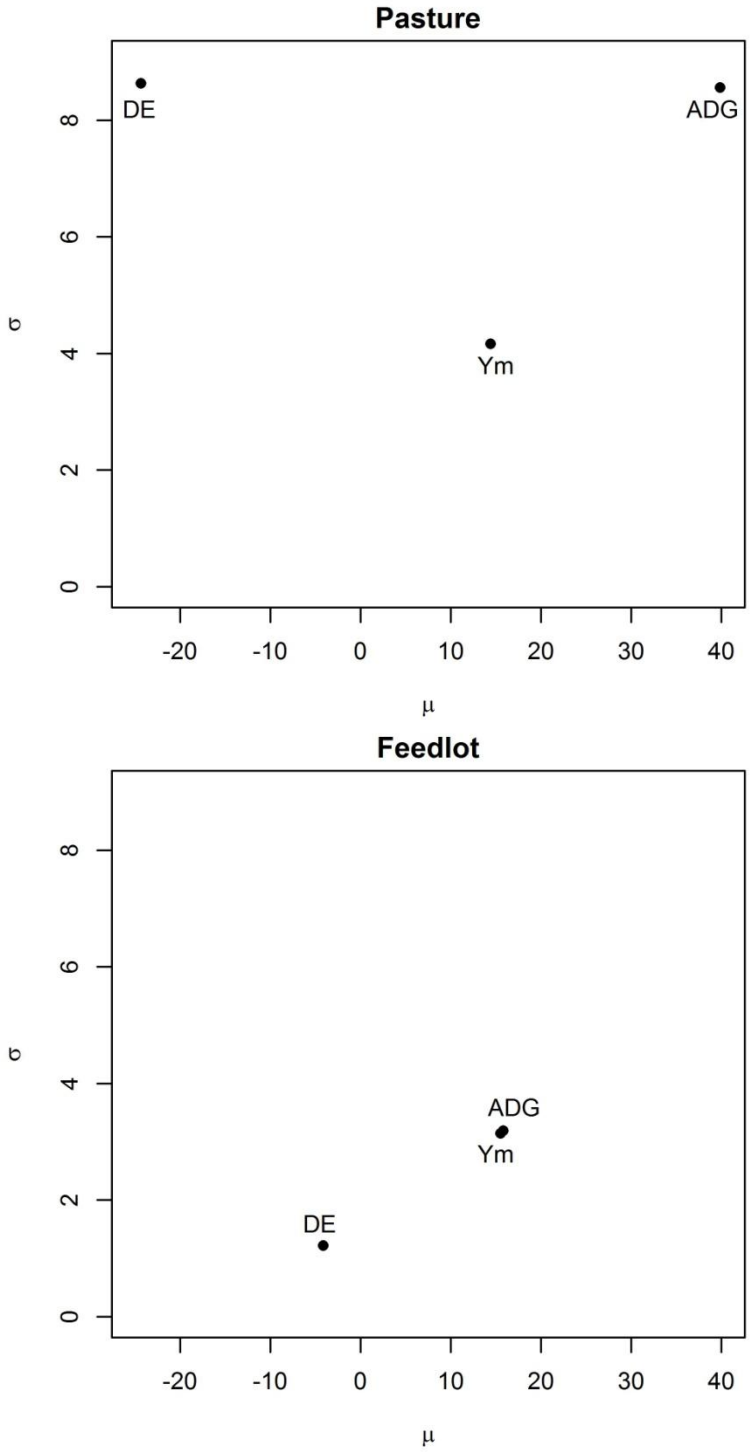


Figure 2-8. Morris indexes for the enteric fermentation emission model (IPCC, 2006). ADG = average daily gain, kg animal^{-1} day^{-1}; DE = digestible energy, %; Ym = methane conversion rate, %.

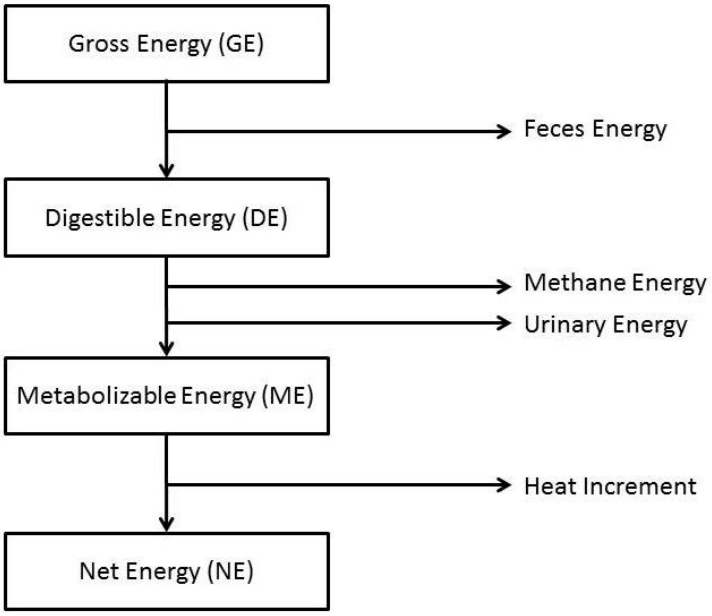


Figure 2-9. Energy partitioning in animals. Adapt from: (Minson, 1990, Van Soest, 1982).

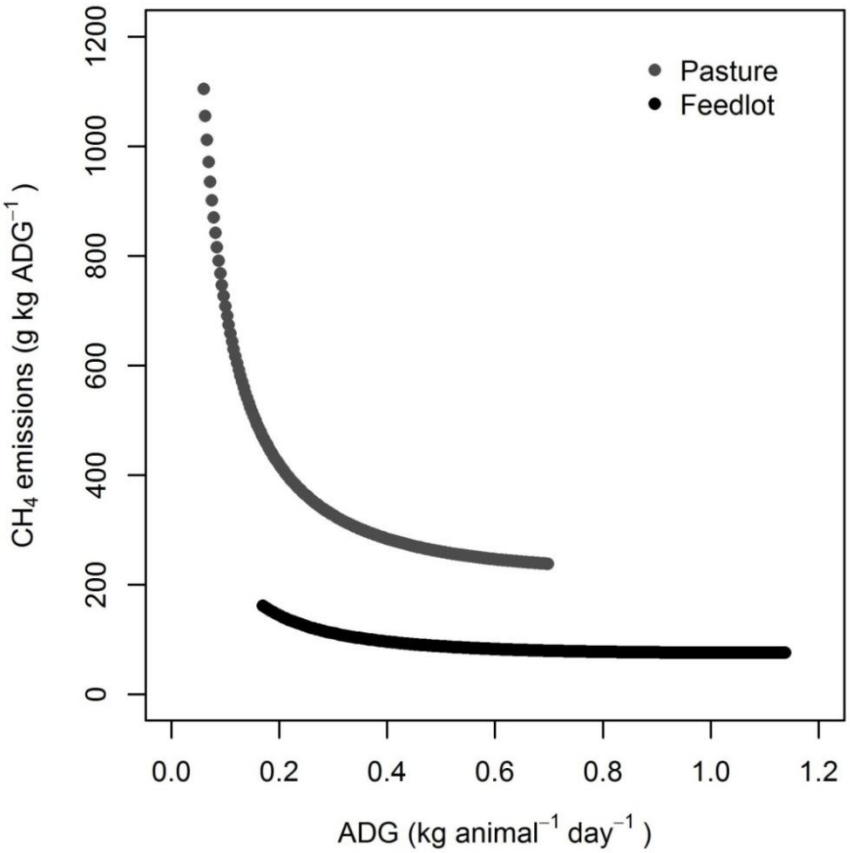


Figure 2-10. Relationship between ADG (kg $animal^{-1}$ day^{-1}) and methane production (g CH_4 ADG^{-1}) for simulations made with Tier 2 enteric fermentation model (IPCC, 2006) for animals on pasture and feedlot.

CHAPTER 3
RUMINAL METHANE EMISSIONS, FORAGE AND ANIMAL PERFORMANCE RESPONSES TO DIFFERENT STOCKING RATES ON CONTINUOUSLY STOCKED BAHIAGRASS PASTURES

Literature Review

Bahiagrass (*Paspalum notatum*) is an important pasture species in the US and is cultivated in a large area in the country, from southern regions to east Texas and central Tennessee. This species covers over 2 million hectares in the southern USA (Newman et al., 2011) and over one million hectares in Florida (Chambliss and Sollenberger, 1991). In north Florida, bahiagrass growing season extends from April to November while in the southern part of the state bahiagrass grow mainly from March to mid-December (Chambliss and Sollenberger, 1991).

Bahiagrass is adapted to a wide variety of soil types and soil pH (Chambliss and Sollenberger, 1991; Twidwell et al., 1998) and climates (Chambliss and Sollenberger, 1991). It is a warm-season perennial grass that reproduces by seed (Burton, 1955) and it can achieve 225 to 560 kg of seed ha^{-1} when properly managed (Chambliss and Sollenberger, 1991). It has a prostrate habit with shallow rhizomes (Newman et al., 2011). Bahiagrass can be used for the production of hay and grazing and is able to support heavy grazing at low soil fertility levels (Twidwell et al., 1998), presenting high persistence and being easily established (Burton, 1955). In Florida, bahiagrass is mostly used for beef cattle (Chambliss and Sollenberger, 1991). Sollenberger et al. (1989) found an ADG of 0.41 kg $head^{-1}$ day^{-1} for beef steers on bahiagrass but encountered a large decrease in ADG in August and September.

Ruminants have one forestomach separated into three compartments called reticulum, rumen and omasum. In the rumen, the anaerobic fermentation of feed occurs as different microbes use the feed to produce volatile fatty acids (VFA) that

are absorbed by ruminants. They also possess a secretory stomach called the abomasum where protein is hydrolyzed and bacteria are digested. The fermentation that occurs in the forestomach breaks down cellulose, which is used as a nutrient by ruminants, and allows for access to cell contents (Leek, 2004). Methane accounts for 30 to 40 % of gases produced during enteric fermentation in ruminants (Leek, 2004), and it can be eliminated through eructation, the lungs or the anus. Around 94- 96% of the CH_4 produced in the rumen is eliminated through eructation, whereas the remaining CH_4 is eliminated through the lungs. The CH_4 produced in the animal's hind gut sums to 10% of total CH_4 produced and is mainly excreted through the lungs (89%), with a small part being eliminated via the anus (11%) (Murray et al., 1976).

The microbial population inside the rumen is composed of different microorganisms. The primary bacteria degrade cellulose or starch, while secondary bacteria use end products from primary bacteria to obtain energy. Protozoa use several substrates as the energy sources, including starch, polyunsaturated fatty acids and ruminal bacteria. The function of fungi in the rumen is yet not well understood. Microbes use mainly hydrolysis and anaerobic oxidation (removal of hydrogen) reactions to obtain energy, creating a need for other reactions that use this hydrogen. This need is fulfilled by methanogenic reactions (Leek, 2004), mediated by obligate anaerobic microorganisms from the *Archaea* family. In the rumen, hydrolysis of cellulose and hemicellulose releases glucose, which is then fermented (Demeyer and Fievez, 2000). Because this reaction occurs in an anaerobic environment, it needs electron receptors other than oxygen for regenerating reaction co-factors like NAD^+, $NADP^+$ and FAD^+ through oxidation, which guarantees that the substrate will continue to be oxidized. However, the

oxidation of the co-factor is inhibited by the presence of H_2 in the rumen. Methanogenic bacteria use the hydrogen to produce CH_4, thus eliminating it from the ruminal environment and allowing for the re-oxidation of co-factors (Demeyer and Fievez, 2000). Production of H_2 also occurs from the oxidation of pyruvate into acetate by the S organisms (Bryant et al., 1967) and is used by methanogenic bacteria to reduce CO_2 and produce CH_4. Experiments suggest that the presence of methanogenic bacteria improves the metabolism of pyruvate (Reddy et al., 1972). The CO_2 used in this reaction comes either from the decarboxylation reactions that occur during fermentation or from the neutralization of the H^+ by HCO_3^- (Leek, 2004). The reactions that produce or use hydrogen inside the rumen are as follows (Ørskov et al., 1968; Moss et al., 2000):

$$\text{Glucose} \rightarrow 2 \text{ pyruvate} + 4H$$

$$\text{Pyruvate} + H_2O \rightarrow \text{acetate} + CO_2 + 2H$$

$$\text{Pyruvate} + 4H \rightarrow \text{propionate} + H_2O$$

$$2 \text{ acetate} + 4H \rightarrow \text{butyrate} + 2H_2O$$

$$CO_2 + 8H \rightarrow CH_4 + 2H_2O$$

One mole of glucose can form two moles of acetic acid, two moles of propionic acid or 1 mole of butyric acid, as seen above. The production of CH_4 in the rumen requires the presence of hydrogen to reduce CO_2. The formation of propionic acid utilizes hydrogen hence reducing CH_4 production, whilst increasing acetate formation in the rumen leads to an increase in available hydrogen for CH_4 production (Ørskov et al., 1968). The acetate to propionate ratio is a good indicator of methanogenic potential in diets. Forage fed cattle can have an acetate:propionate ratio up to 4:1, while animals on grain diets have an acetate:propionate ratio of 1:1 (Russel, 2002).

There are different techniques used to measure CH_4 emissions from ruminants, each having advantages and disadvantages and being more adequate for specific experimental conditions (Storm et al., 2012). These are the SF_6 tracer gas technique (Johnson et al., 1994), the open- circuit chamber technique (Brown et al., 1984), the tunnel technique (Murray et al., 1999), micrometeorological mass difference (Harper et al., 2011) and the *in vitro* technique (Storm et al., 2012). A brief description of these follows.

The sulfur hexafluoride (SF_6) tracer technique is used to estimate CH_4 emission rates by ruminants in production conditions, including grazing (Johnson et al., 2007), and is useful to assess several aspects of feeding and nutrition such as influence of chemical and physical feed composition or additives on CH_4 emissions (Storm et al., 2012). It is important to notice that this technique does not measure CH_4 produced in the hindgut that is not absorbed by the bloodstream (Johnson and Johnson, 1995). Some of the advantages of the SF_6 tracer technique summarized by Storm et al. (2012) are that animals are allowed to move freely when carrying the equipment, so that this technique can be used during grazing trials on which animal performance data is also measured. Also, the results are useful to analyze variation in CH_4 emission rates within and between animals and can be related to production aspects such as milk yield and weight gain. The technique can be used to assess almost all feeding aspects important in animal production. Studies comparing the SF_6 tracer technique with chamber measurements (technique described below) found no significant difference among these methods (Johnson et al., 1994, 2007). In addition, animal acclimation for the use of the SF_6 tracer technique takes some days to a week, a short period of time when compared with the weeks necessary for the use of calorimetry chambers (Johnson et al., 1994). However, Storm et al. (2012)

emphasize that this technique is not suitable to evaluate differences in the emissions through the day and that the results are more variable than in experiments made using chambers, hence more animals are necessary when performing animal CH_4 measurements using this technique.

Chambers used in CH_4 measurements can be of the open or close circuit types (Storm et al., 2012). Open-circuit indirect calorimetry chambers are used to analyze how modifications in nutritional state, activities or environmental temperature affect the metabolic rate of living beings during a short period (Brown et al., 1984). When used to measure CH_4 emissions by animals, this method is useful to analyze nutrition and feeding influence on emissions and can be used to obtain results of emissions of CH_4 throughout the day (Storm et al., 2012). With this methodology, measurements are obtained using infra-red or paramagnetic analyzers that give results proportional to the molecular density of the gas. These measurements are used in a series of equations to estimate volume of gas and corrected to conditions of temperature and pressure (STP). The rate of increase of the volume of a given gas inside the chamber is calculated as the sum of rate of volume production and flow of the gas inside the chamber minus the rate of volume flow outside the chamber (Brown et al., 1984). When measuring CH_4 emission rates using open-circuit respiration calorimetry chambers, the concentration of CH_4 is analyzed in the air that comes in and out the chamber constantly during the experimental period using infrared analyzers (Johnson et al., 1994). Among the difficulties presented by the use of the chamber methods in CH_4 emission evaluations are the training necessary for animal's acclimation to the chamber, a process that can take several weeks and the chamber's high cost. Also, restrictions to the animal's natural

behaviour may make this method unsuitable for extrapolation to real production situations (Johnson et al., 1994).

Similar to the chambers, the tunnel methodology analyzes the air flowing in and out of a tunnel for CH_4 concentration, air speed and temperature (Murray et al., 1999). This system was designed to provide animals with an environment as similar to natural conditions as possible (Lockyer and Jarvis, 1995). When using this methodology CH_4 emissions by animals seem to be lower than other estimates (Lockyer and Jarvis, 1995; Murray et al., 1999).

Another technique useful to measure CH_4 emissions from animals in either grazing or feedlot conditions is the micrometeorological mass difference approach, where the flux of gases of interest in the free atmosphere is measured while maintaining animals in their natural environment (Harper et al., 2011). This technique requires less animal handling, therefore the animals maintain their natural behavior (Harper et al., 2011). In this technique CH_4 concentration in the air is analyzed using infrared gas analysis or gas chromatography at different heights around the area frequented by animals under study. This information combined with data on wind speed and direction provides values of CH_4 flux (Harper et al., 1999). The micrometeorological technique is useful for analyzing production systems, however little is known about its reliability (Storm et al., 2012).

The *in vitro* technique is a rapid and low-cost approach when assessing how additives influence CH_4 emissions because it is fast and relatively inexpensive. In this procedure, feeds are incubated in a container with a medium combining rumen fluid, a buffer solution and minerals. Data on CH_4 production are obtained from the analysis of gas composition and production 24 hours after incubation, usually. Degradation of feed must be analyzed to guarantee that CH_4 production is not

decreased because of decreased feed degradation (Storm et al., 2012). Bhatta et al. (2008) analyzed CH_4 emissions by goats fed at 1.1 times maintenance with nineteen different diets using open circuit respiration chambers and *in vitro* methodology. The authors found that emissions from both methodologies were quite similar particularly for diets with high proportions of structural carbohydrates. Feeding Holstein cows at a maintenance level with five different diets, Bhatta et al. (2006) found correlation values between the SF_6 tracer and *in vitro* gas production technique of 0.75 and 0.94 for incubations of 24 and 48 hours, respectively.

Many factors affect CH_4 production by cattle, including manipulation of the diet fed to animals (processing, addition of lipid to diet, type of carbohydrate offered in feed), modification of ruminal microflora and management of animal intake (Johnson and Johnson, 1995), on which animal performance is greatly dependent (Poppi et al., 1997). Martin et al. (2009) affirm aspects that should be considered in mitigation strategies are the decreased in H_2 production in the rumen while maintaining feed digestion, modifying the end products from the H_2 utilization reactions and inhibiting methanogenic bacteria. Animal breeding has also been suggested as an alternative to reduce CH_4 emissions from ruminants not only directly, but also by improving animal efficiency (conversion of feed into products like meat and milk), productivity (reducing the number of animals needed for production) and reduction of losses such as empty reproductive cycles (Wall et al., 2009).

Some work has focused on feed manipulation for decreasing CH_4 production in ruminants by the use of additives. Bhatta et al. (2008) found several by-products that reduced CH_4 emissions in goats, such as pumpkin and brewer's grains and sweet potato vine silage. Tannin has also been studied and resulted in lesser CH_4 emissions in goats (Puchala et al., 2005) and sheep (Carulla et al., 2005), but tannin

had no effect on cattle in reducing emissions, where it had bound protein (Beauchemin et al., 2007). Other additives like canola oil reduce CH_4 production in ruminants but negatively affect animal intake and fiber digestibility, thus possibly affecting animal performance (Beauchemin and Mcginn, 2006). Moe and Tyrrell (1979) suggested that the nature of carbohydrates in ruminant diets can affect production of CH_4 particularly at intakes higher than 1.5 times maintenance. Increases in digestible cellulose in diets can drive fermentation from the formation of propionate to methanogenesis. According to Russel (2002), access to cell contents can be decreased by the presence of lignin in the plant's fiber, which microbial cellulases cannot break. The presence of lignin can also hinder rumination and therefore decrease feed particle reduction. Production of CH_4 was found to be positively related to apparent cellulose digestibility (Pinares-Patio et al., 2003) and to type of carbohydrates in high intake diets (Moe and Tyrrell, 1979).

Animal CH_4 measurements have also been performed in grazing trials, where management practices and pasture species effect on CH_4 emissions were investigated. McCaughey et al. (1999) found lower emissions for animals grazing alfalfa (*Medicago sativa* L.)/grass (meadow bromegrass, *Bromus biebersteinii* Roem and Schult) than for animals grazing on grass only (meadow bromegrass, *Bromus biebersteinii* Roem and Schult). Kurihara et al. (1999) found that emissions were higher for heifers eating mature angletongrass (*Dicanthium aristatum*) with lower N content than for those grazing on rhodes grass (*Chloris gayana*) with medium digestibility and N content. Some studies have analyzed grazing management's effect on CH_4 emissions. The use of BMPs (intensive grazing, rotational stocking rate, overseeding ryegrass and fertilization) was found to result in lower CH_4 production when animals were grazing on bahiagrass and bermudagrass (Kurihara

et al., 1999). McCaughey et al. (1997) found a significant difference in CH_4 emissions when studying animals on continuously stocked alfalfa-grass (Roem and Schult, *Bromus biebersteinii*; Russian wildrye, *Psathyrostachys juncea* (Fisch.) Nevski) at two stocking rates. In that study, the treatment with higher stocking rate had lower CH_4 day^{-1} when compared to lower stocking rates. However, management strategies and their effect on CH_4 emission still need further investigation. Despite the importance of the beef industry in Florida, no measures of CH_4 emissions for animals on pasture exist in this state.

The objective of this study was to measure CH_4 emissions, animal performance and forage characteristics of animals continuously stocked on bahiagrass pastures at three stocking rates.

Materials and Methods

Experimental Site

This experiment was carried out during the summer of 2012 at the North Florida Research and Education Center (NFREC) in Marianna (Jackson County), Florida (Latitude: 30° 42’ N Longitude: 85° 13’ W). The area used for the experiment had bahiagrass established in 2010 and was previously used for evaluations of herbage production under different N applications. In April 2012 the area was evenly fertilized with 57 kg ha^{-1} of N from ammonium nitrate (NH_4NO_3). The experimental area was located in two experimental sites Figure 3-1. Soil types at the experimental sites are described on Table 3-1 The climate in the region where the experiment was conducted is classified as warm temperate, fully humid with hot summers (Cfa) according to the Köppen-Geiger classification (Kottek et al., 2006).

Treatments and Design

The treatments in this experiment were defined as stocking rates (SR) of 1.2, 2.4 and 3.6 AU ha^{-1} where one animal unit (AU) is 470 kg. The bahiagrass pastures were continuously stocked under the described fixed stocking rates during the grazing season of 2012, meaning that a fixed number of animals was kept in each experimental unit during the entire experimental period. The animal's initial liveweight was 347 ± 29 kg and it was estimated that animal average daily weight gain would be approximately 0.46 kg/day (Stewart, 2003) during a 84-day period, which would result in an average weight of 366 kg in the experimental period. Each experimental unit was 1.3 ha in area. To achieve the target SRs of 1.2, 2.4 and 3.6 AU ha^{-1} the number of animals used was 2, 4 and 6 animals $pasture^{-1}$. These treatments were chosen with the objective of achieving differences in animal intake and were determined on the estimated carrying capacity of the pastures according to the N fertilization rates applied in the experimental area (57 kg N ha^{-1}), based on Twidwell et al. (1998) and Stewart (2003).

The experiment was initiated on 25 June and ended on 18 September 2012. This time included three equal periods of 28 days each (Period 1: 25 June to 22 July; Period 2: 23 July to 19 August; Period 3: 20 August to 18 September). The experimental units were arranged in two blocks located in adjoining areas. Each block contained 6 pastures of 1.3 ha, and so the total number of experimental units was 12. The three treatments were replicated four times such that two replicates of a treatment were randomly assigned to each block (randomized complete block).

Pasture and Animal Management

Herbage mass, herbage accumulation and herbage nutritive value were measured. Herbage mass was estimated using the double sampling technique which

associates direct and indirect measurements of herbage mass (Santillan et al., 1979). The indirect measurement was taken using a disk meter, where a 0.25 m^2 aluminum disk was dropped always from the same height and settling height recorded. Every 28 days, three sites representing low, medium and high herbage mass were sampled per experimental unit. At these sites, disk meter settling height was measured (indirect measurement) and with the help of a circular quadrat with the same area of the disk the forage beneath the disk was clipped (direct measurement). The pasture samples were dried at 60°C until constant weight (48 to 72 hours). Calibration equations were obtained for each of the three sampling dates with disk height as a dependent variable to herbage mass (Table 3-2). Every 14 days, disk meter settling height was measured at 30 locations per pasture, with sampling units separated by the same number of steps in each experimental unit. Average disk meter settling height was inputted in the calibration equation to estimate herbage mass.

To estimate herbage accumulation rate (HAR), three 1 m^2 exclusion cages were installed per pasture at the beginning of the experimental period at sites where the disk meter measurements were ±1 cm from average disk meter measures for that pasture. Every 14 days, disk height was measured inside the cage. The cages were then relocated to sites in the pasture that had the same disk settling height (±1 cm) of the rest of the pasture. Herbage mass was estimated using the calibration equation for the period. Herbage accumulation rate was calculated as follows:

$$HAR\ (kg\ ha^{-1}\ day^{-1}) = [Cage\ HM\ (kg\ ha^{-1})_{\ day\ 2} - Cage\ HM\ (kg\ ha^{-1})_{\ day\ 1}] / days$$

Every 14 days, one sample composed of 20- 25 hand plucked subsamples per pasture was collected and used to measure nutritive value (crude protein, CP; neural detergent fiber, NDF; acid detergent fiber, ADF). After collection, the samples

were dried at 60 °C for 48 to 72 hours and ground to pass through a 1-mm screen. Data regarding herbage information for each period was obtained by taking the mean of values on days 1, 14 and 28 for each period.

Animals (cross bred heifers) were weighted every 28 days in the morning after 16 hours of fasting. Data were then used to calculate animal performance as animal daily weight gain (ADG, kg day^{-1}) as

ADG (kg day^{-1}) = (final weight – initial weight) / 28 days

Animal intake was estimated using the disappearance of herbage mass technique (Moore and Sollenberger, 1997), where the difference in dry herbage mass (HM) in grazed and ungrazed areas for a specific period of time are calculated to estimate how much forage is taken in by the group of animals in the pasture:

Animal daily DM intake = {[(Available HM) – (Residual HM)] / (period) / (SR)

Animal intake was estimated every 14 days. Measurements of herbage mass taken inside the exclusion cages represented ungrazed areas or available HM and measurements of herbage mass taken outside the exclusion cages were from grazed areas or residual dry HM. Therefore

Animal daily DM intake = {[(Available DHM) – (Residual DHM)]/ (period)/ (SR)

where

Animal daily DM intake = kg day $^{-1}$;

Available HM = kg HM ha^{-1};

Residual HM = kg HM ha^{-1};

Periods = 14 days;

SR = stocking rate, AU ha^{-1}.

Three weeks after the beginning of the experiment (by 17 July) the treatments did not show differences in forage characteristics. Since the objective of the study

was to use SR to create differences in forage characteristics and study their effects on CH_4 production by animals and animals performance, 1, 2 and 3 AU ha^{-1} were added to the experiment in the treatments 1.2, 2.4 and 3.6 ha^{-1}, respectively. These animals remained in the experimental units for three weeks. Animal weight data from these animals were not considered in the analysis of average daily gain.

Ruminal Methane Emissions Measurements

Two CH_4 collection periods occurred starting 8 July and 10 September 2012 using the technique described in Johnson et al. (2007). One collection period consisted of five consecutive days of measurements and results of CH_4 production per day were averaged to obtain one value per animal per period. Methane emission rate was also averaged between the animals within each experimental unit. Twenty four animals previously used in another experiment for CH_4 measurements were used in this study so that two animals per experimental unit were used for the CH_4 measurements. In these animals, one permeation tube with a known SF_6 released rate was placed in the animal's rumen. These permeation tubes were purchased from Washington State University, where they were calibrated in hot water bath at 39 °C to achieve a constant release rate of between 1 and 2 mg day^{-1}. Average SF_6 release rate was of 1.7597 mg day^{-1}. The collection of air around the animal's mouth and nostrils was made through a capillary tube place on the top of the animal's nose. This capillary was attached to a halter and is connected through a valve to a PVC canister evacuated to -27 mm Hg (Figure 3-2). Samples were collected to a pressure of -13.5 mm Hg. Data from canisters returning with pressures above -10 mm Hg or below -20 mm Hg were not considered. Any animals which did not have at least three days of collection were not considered in the analysis. Collection time to achieve the final pressure was 24 h and was regulated by the length of the capillary

tube. In the first day of each collection period a halter and an evacuated yoke were placed on the animals. After 24 h, the yoke collecting the sample was retrieved and a new, evacuated canister was placed on the animals, connected to the yoke, and the valve was opened. This procedure was repeated for five consecutive days. On every collection day, two canisters were used to collect air and one placed at the center of each experimental area (A and B Figure 3-1) that served to analyze background (ambient) concentrations of CH_4 and SF_6.

The canisters containing the sample were taken to the lab for analysis lab and allowed to cool until they reached environmental temperature. They were then pressurized with N until 3 psi and CH_4 and SF_6 concentrations were measured twice from each canister using gas chromatography (Agilent 7820A GC, Agilent Technologies, Palo Alto, CA) equipped with a flame ionization detector and a capillary column (Plot Fused Silica 25 m × 0.32 mm, coating Molsieve 5A, Varian CP7536).

Every collection day, pure standards were used to obtain a calibration curve for CH_4 and SF_6. After this, the canisters were rinsed ten times with pressured air. To obtain the values of g CH_4 day^{-1}, the following equation was used:

$$QCH_4 = QSF_6 \times [(CH_4 - CH_{4\,A}) / (SF_6 - SF_{6\,A})]$$

where

QCH_4 is CH_4 emissions rate, g day^{-1};

QSF_6 is the SF_6 release rate

CH_4 and SF_6 are the concentration in the yoke

$CH_{4\,A}$ e $SF_{6\,A}$ are the concentrations in the ambient.

The correction for background SF_6 concentrations were followed as suggested by (Lassey, 2013). QCH_4 outliers (mean ± 2 SD) were eliminated.

Statistical Analysis

Statistical analysis was performed using SAS. Response variables were herbage mass (HM), herbage accumulation rate (HAR), CP, ADF, NDF, average daily gain (ADG), body weight (BW), dry matter intake (DMI) (kg animal^{-1} day^{-1}, kg kg BW^{-1} day^{-1}) and CH_4 (g CH_4 day^{-1}, g CH_4 kg BW^{-1} and g CH_4 kg DMI^{-1}). Data were analyzed using repeated measures analysis of variance using PROC MIX model of SAS. Periods were considered repeated measures and pasture (experimental unit) was considered to be the experimental unit. SR, period and SR x period were fixed effects. Block and interactions with block were considered random.

Results

Results of the effect of treatment (different SR on continuously stocked bahiagrass), period and treatment x period interaction are summarized in Table 3-3. Forage nutritive value was affected by period but no treatment or treatment x period effect were observed on animal or plat related response variables. There was no effect of treatment or period on animal related variables, including the measures of CH_4 (g CH_4 day^{-1}, g CH_4 kg BW^{-1} and g CH_4 kg DMI^{-1}).

Discussion

The values of HM (presented on Figure 3-3) found in this study are similar to those previously reported in the literature. Chambliss and Sollenberger (1991) reported values varying between 2600 and 6330 for the summer in Florida. There was an increase in HM through the grazing season with higher values observed in August. This pattern was different than that observed by others (Johnson et al., 2001b; Stewart, 2003), where HM peaked by the end of June and July. The difference might be related to the rainfall pattern observed during the experimental period. In July, rainfall was 139 mm and reached 367 mm in August. There was no

effect of treatment or period in HAR. Values of HAR ranged from 57 to 67 kg HM ha^{-1} day^{-1}. These values are in the range of previously reported studies. Inyang et al. (2010) found values of 106, 128 and 118 kg HM ha^{-1} day^{-1} on continuously stocked bahiagrass. The lower HAR observed might have been caused by the lower rainfall observed in the months of June and July in the present study. Stewart Jr. (2003) evaluated bahiagrass under low, moderate and high management (1.2, 2.4 and 3.6 AU ha^{-1} with applications of 40, 120 and 360 kg N ha^{-1}, respectively). The author found significantly higher HAR at moderate and high management treatment achieving values of as high as 37 kg ha^{-1} day^{-1}. At low management levels, average HAR was 19 kg ha^{-1} day^{-1}.

A tendency to treatment effect and an effect of period were observed for values of CP, but no treatment x period interactions were observed (Figure 3-10). Period also had a positive effect on CP with values 8.8, 9.2 and 9.5% Periods 1, 2 and 3, respectively. Values of CP between 9.9 and 12% were reported for rotationally stocked bahiagrass, with values increasing after September (Sollenberger et al., 1989). On continuously stocked bahiagrass, Stewart (2003) found values of CP varying between 9.2 and 14.3% with significantly higher values of CP with more intense management (higher SR and N fertilizer application). Cuomo et al. (1996) evaluated the nutritive value of Argentine and Pensacola bahiagrass under different cutting frequencies (20, 30 and 40 days) in two years. Values reported by Cuomo et al. (1996) were of 14% and 10% for CP in early (late May to end of June) and late (mid-August to mid-September).

For NDF, no treatment effect was observed. There was a period effect on NDF which increased through the grazing season (Figure 3-9). Other authors also found an increase in NDF concentration of bahiagrass through grazing seasons.

NDF increased through the grazing season from the range of 73 to 86% to the range of 79 to 82% (Grise et al., 2006). These values are higher than those observed in the present study. However, the values presented by Grise et al. (2006) refer to whole-plant samples and do not represent the grazed proportion of the pasture. In this case, nutritive value might be underestimated (Sollenberger and Cherney, 1995).

There was no effect of treatment on ADF, but a period effect was observed with increasing ADF concentration as the season progressed. Other studies have also found differences in ADF through grazing season in bahiagrass. Cuomo et al. (1996) found lower values of ADF for bahiagrass in early summer (May to June). .

No effect of SR or period on ADG was observed. The ADG was lower than what has been observed for continuously stocked bahiagrass with values varying between 0.22 to -0.18. Inyang et al. (2010) observed a linear decrease in ADG with increasing of SR (4, 8 and 12 heifers ha^{-1}). Low ADG of animals grazing bahiagrass and bermudagrass was also observed during summer and fall by DeRamus et al. (2003). Sollenberger et al. (1989) found an ADG of 0.41 kg $head^{-1}$ day^{-1} when crossbred yearling steers grazed on bahiagrass from April through November but encountered a large decrease in ADG in August and September. Stewart (2003) evaluated bahiagrass under low, moderate and high management (1.2, 2.4 and 3.6 AU ha^{-1} with applications of 40, 120 and 360 kg N ha^{-1}, respectively) and found that ADG decreased with higher management levels. However, gain per hectare in that study was smaller at low management levels.

There was no effect of SR or period on DMI expressed as kg $animal^{-1}$ day^{-1} or kg $(kg\ BW)^{-1}$ day^{-1}. Values of DMI (kg $animal^{-1}$ day^{-1}) found were higher than expected achieving values as high as 22 kg $animal^{-1}$ day^{-1}. Undi et al. (2008) compared the use of herbage mass disappearance technique with the use of

alkanes and two prediction equations for measuring intake. The author found that estimation of DMI using the herbage disappearance technique was greater than any of the other techniques, achieving values of 14.3 to 18.9 kg DMI day^{-1}. The authors suggest that the trampling of the pasture might be the cause of this overestimation of DMI. It has been found that DMI is linearly related to CH_4 emissions (g $animal^{-1}$ day^{-1}) for cattle grazing tropical forages (Kurihara et al., 1999). However, no linear or quadratic relationship was found between CH_4 (g day^{-1}) and DMI (kg $animal^{-1}$ day^{-1}).

There was no effect of treatment or period on CH_4 emissions expressed as g CH_4 day^{-1}, g CH_4 kg BW^{-1} and g CH_4 kg DMI^{-1} (Figure 3-11, Figure 3-12 and Figure 3-13). The coefficient of variation (CV, %) within animals was 79 and 86% in the first and second periods of CH_4 collection. Although these CVs are higher than those reported in the literature, large variation in CH_4 production between animals has been reported in other studies using the SF_6 technique. In sheep fed chaffed lucerne hay diets, between individual variation was responsible for 70% of variation in CH_4 production (Pinares-Patio et al., 2003). In cattle fed different forages with different qualities, CV (%) values for CH_4 emission above 26% were observed in both day- to-day and animal- to- animal measurements (Boadi et al., 2004). However, the authors emphasized that these high values might be related to the diverse feeding conditions and small number of animals. This large CV is one of the reasons why no statistical differences between treatments or periods were detected.

The values of CH_4 emissions varied between 140 to 879 g CH_4 day^{-1}. The values found in the present study were higher than what was previously reported for animal grazing bahiagrass. For animals grazing bahiagrass under normal or BMP management (overseeding of ryegrass and fertilization), lower values of CH_4 emissions were found under BMP management (DeRamus et al., 2003). Values of

daily CH_4 emissions for cows and heifers of 120 to 249 g day^{-1} and 86 to 166 g day^{-1} were reported (DeRamus et al., 2003). High values of CH_4 emissions were found for dairy cattle and lactating beef cattle. For dairy cattle grazing perennial ryegrass and white clover, Ulyatt et al. (2002) found varying values of CH_4 emissions through the season between 137 and 431 g day^{-1}. The seasonal variation was closely related to milk production and estimated animal intake. For lactating beef cattle grazing alfalfa-grass or bromegrass pastures, CH_4 emissions of 267- 293 g day^{-1} were reported (McCaughey et al., 1999). McCaughey et al. (1997) found a difference in CH_4 emissions when studying animals on continuously stocked alfalfa (*Medicago sativa*)-grass (Roem and Schult, *Bromus biebersteinii*; Russian wildrye, *Psathyrostachys juncea* (Fisch.) Nevski) with two stocking rates. In that study, the treatment with higher stocking rate had lower CH_4 day^{-1} when compared to lower stocking rates. Kurihara et al. (1999) suggested that the CH_4 conversion rate of tropical forages is higher than those from temperate species, i. e., more energy is used in the production of CH_4 when animals are fed tropical forages.

Although some authors conclude that DM intake can be used to predict CH_4 production by adult cattle on maintenance (Moe and Tyrrell, 1979), more studies are necessary to confirm if the linear relationship between DM intake and CH_4 emissions (g $animal^{-1}$ day^{-1}) for cattle grazing tropical forages may be used for prediction (Kurihara et al., 1999). In that study, authors found that CH_4 emission rate is reduced at high feed levels and energy intake in comparison to animals kept on maintenance level, probably due to greater rate of passage of feed in the animals' digestible tract and consequent reduction in feed fermentation time. This difference in CH_4 energy according to animal's feeding level was also observed by Moe and Tyrrell (1979) in dairy cattle, and the authors concluded that type of carbohydrate influences CH_4 in

dairy cattle at higher intakes but do not significantly affect CH_4 prediction at lower intakes. Another study conducted by Boadi and Wittenberg (2002) where animals were fed hay varying in IVOMD concluded that DM intake could be used to predict CH_4 emissions from animals fed *ad libitum*, and DMI represented 64% of variation in CH_4 emissions. Although several studies show a relationship between CH_4 emissions and intake, there was no correlation of these two variables in this study.

Information on initial weight and ADG of each treatment on Periods 1 and 3 were used in the IPCC (Tier 2) method to estimate emissions in g CH_4 day^{-1}. Results are presented in Figure 3-14, where the default value suggested by IPCC (2006) for the Tier 1 method is also presented. It is evident that the values from the field measures were much more variable than that obtained using the Tier 2 approach. Results obtained by the Tier 2 approach do not differ greatly due to treatment. This is probably related to the very similar ADG values encountered in the field experiment and used in the simulation, since it was found that the model is very sensitive to the ADG variable. The Tier 1 and Tier 2 approaches seem to underestimate CH_4 emissions in this study, however a more detailed study on prediction capacity is necessary.

Conclusions

The objective of this study was to measure CH_4 emissions, animal performance and forage characteristics of animals grazing continuously stocked bahiagrass under three different stocking rates. The SR applied affected HM and chemical value of bahiagrass, however it did not affect animal response variables. CH_4 emissions were also not affected by SR. On average, animals grazing bahiagrass emitted 393 g CH_4 day^{-1} and a high variation was found on emissions. This is the first CH_4 measurements for grazing animals in Florida. The IPCC Tier 2

and Tier 1 approaches seem to underestimate emissions of CH_4 by cattle. Due to the great importance of agriculture in Florida's economy, it is important to obtain more information about emissions from different agriculture-related sources. This information may help not only to improve model use but also give a more clear understanding of management approaches that can be used to reduce or avoid GHG emissions.

Table 3-1. Soil types in experimental sites A and B. Source: USDA, 2013.

Map Unit Name	Percentage of area
Experimental site A	
Chipola loamy sand, 0 to 5 percent slopes	2.9
Orangeburg loamy sand, 2 to 5 percent slopes	49.3
Red Bay fine sandy loam, 2 to 5 percent slopes	47.9
Experimental site B	
Fuquay coarse sand, 0 to 5 percent slopes	25.2
Greenville fine sandy loam, 2 to 5 percent slopes	28.0
Orangeburg loamy sand, 2 to 5 percent slopes	46.7
Red Bay fine sandy loam, 2 to 5 percent slopes	0.1

Table 3-2. Herbage mass double sample regression equations. Period 1: 25 June to 22 July; Period 2: 23 July to 19 Aug.; Period 3: 20 Aug to 18 Sep.

Period	Equation	R^2
1	y = 6.3604x + 5.2975	0.87
2	y = 6.6018x – 0.9663	0.89
3	y = 6.8917x + 17.804	0.81

Table 3-3. Effect of stocking rate (1.2, 2.4 and 3.6 AU ha^{-1}) on response variables in 2012 period and treatment x period interaction on experimental variables.

		Treatment	Period	Treatment * Period
HM	(kg ha^{-1})	**	**	**
HAR	(kg ha^{-1} day^{-1})	NS	NS	NS
ADF	(%)	NS	**	NS
NDF	(%)	NS	**	NS
CP	(%)	NS	**	NS
DMI	(kg $animal^{-1}$ day^{-1})	NS	NS	NS
DMI	(kg kg BW^{-1} day^{-1})	NS	NS	NS
ADG	(kg $animal^{-1}$ day^{-1})	NS	NS	NS
BW	(kg)	NS	NS	NS
CH_4	(g CH_4 day^{-1})	NS	NS	NS
CH_4	(g CH_4 kg BW^{-1})	NS	NS	NS
CH_4	(g CH_4 kg DMI^{-1})	NS	NS	NS

NS: non-significant

** : significant at 1% (P<0.01)

Table 3-4. Forage herbage mass (HM) (kg ha^{-1}) and herbage accumulation rate (HAR) (kg ha^{-1} day^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

	Period 1	Period 2	Period 3	
Stocking rate (AU ha^{-1})		HM (kg ha^{-1})		SE
1.2	3235	3956	4787	198.4
2.4	3239	3661	4063	198.4
3.6	2967	2735	2983	198.4
		HAR (kg $ha^{-1}day^{-1}$)		
1.2	67	57	57	8.5
2.4	65	61	59	8.5
3.6	62	57	67	8.5

Table 3-5. Forage chemical composition response given by CP (%), NDF (%) and ADF (%) to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

	Period 1	Period 2	Period 3	
Stocking rate (AU ha^{-1})		CP (%)		SE
1.2	8.6	8.6	8.7	1.5
2.4	8.5	9.0	9.2	1.5
3.6	9.4	10.0	10.8	1.5
		NDF (%)		
1.2	63.2	64.8	65.4	0.6
2.4	63.2	65.6	65.4	0.6
3.6	64.5	64.2	63.6	0.6
		ADF (%)		
1.2	35.1	36.1	37.1	1.0
2.4	35.6	36.9	36.9	1.0
3.6	35.7	36.5	36.4	1.0

Table 3-6. Average daily gain (ADG, kg animal^{-1}day^{-1}), BW (kg animal^{-1}), DMI (kg animal^{-1}day^{-1}) and DMI (kg BWl^{-1} day^{-1}) response to three stocking rates (1.2, 2.4, 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

	Period 1	Period 2	Period 3	
Stocking rate (AU ha^{-1})	ADG (kg animal^{-1}day^{-1})			SE
1.2	0.03	0.12	-0.18	0.2
2.4	0.22	-0.03	-0.03	0.2
3.6	0.12	-0.02	0.01	0.2
	BW (kg animal^{-1})			
1.2	344.9	347.1	349.2	4.7
2.4	348.4	351.0	351.1	4.7
3.6	353.3	355.8	351.9	4.7
	DMI (kg animal^{-1}day^{-1})			
1.2	20	21	22	3.2
2.4	18	16	17	3.2
3.6	15	14	15	3.2
	DMI (kg kg BWl^{-1}day^{-1})			
1.2	5.9	6.0	6.5	0.9
2.4	5.2	4.6	4.9	0.9
3.6	4.1	4.0	4.2	0.9

Table 3-7. Response of CH_4 emissions expressed as g CH_4 day^{-1}, g kg BW^{-1} and g kg DMI^{-1} to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

	Period 1			Period 3		
Stocking rate (AU ha^{-1})	CH_4 (g day^{-1}) ± SE					
1.2	485.3	±	237.3	337.3	±	193.8
2.4	140.3	±	167.8	333.4	±	167.8
3.6	180.1	±	335.6	879.4	±	193.8
	CH_4 (g kg BW^{-1}) ± SE					
1.2	1.4	±	0.7	1.0	±	0.6
2.4	0.4	±	0.5	0.9	±	0.5
3.6	0.5	±	1.0	2.5	±	0.6
	CH_4 (g kg DMI^{-1}) ± SE					
1.2	41.7	±	20.3	13.6	±	16.6
2.4	8.3	±	14.4	22.6	±	14.4
3.6	12.8	±	28.7	70.2	±	16.6

Figure 3-1. Map of experimental sites A and B located at the North Florida Research and Education Center (NFREC), Marianna, Florida.

Figure 3-2. Animal with CH_4 collection device. A: capillary tube placed on halter; B: collecting canister. Picture by Marta Moura Kohmann, 2012.

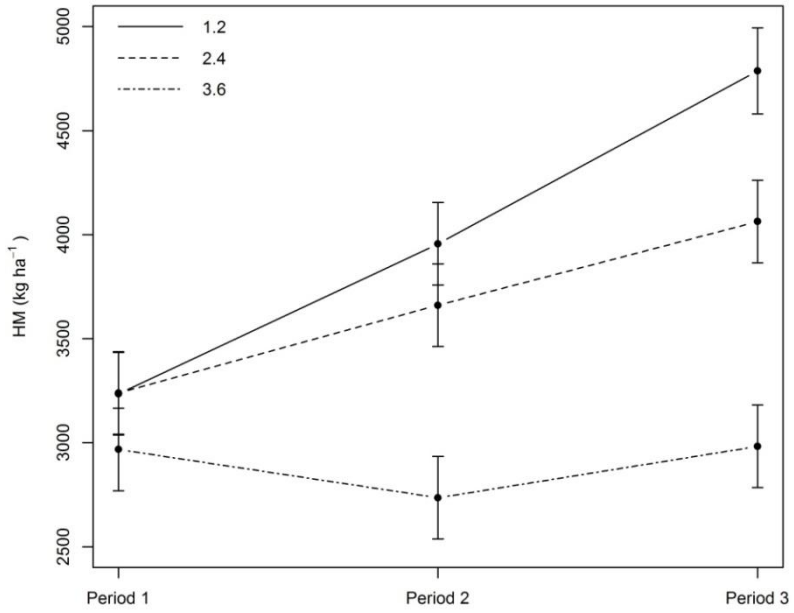


Figure 3-3. Herbage mass (kg ha^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

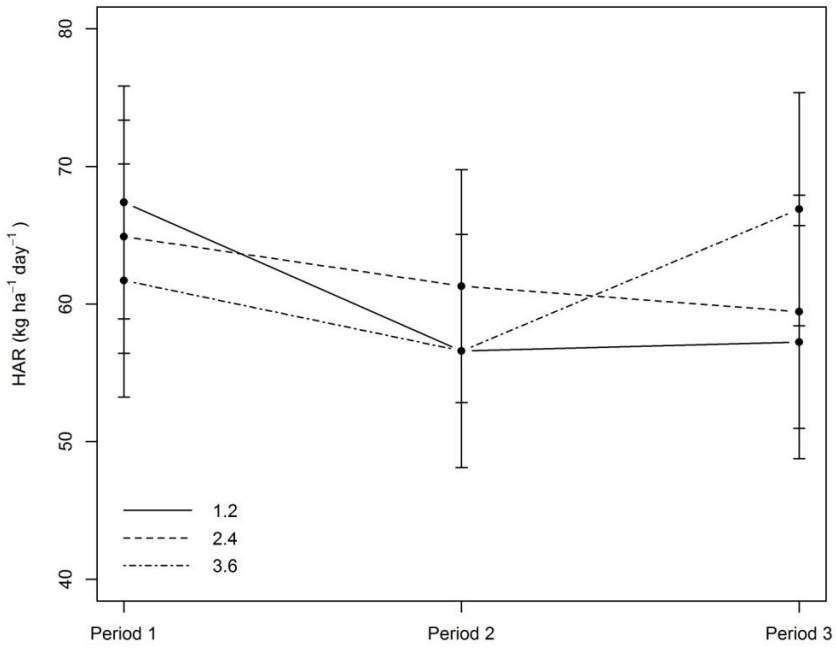


Figure 3-4. Herbage accumulation rate (HAR) (kg ha^{-1} day^{-1}) i response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug. 20 to Sep. 18.

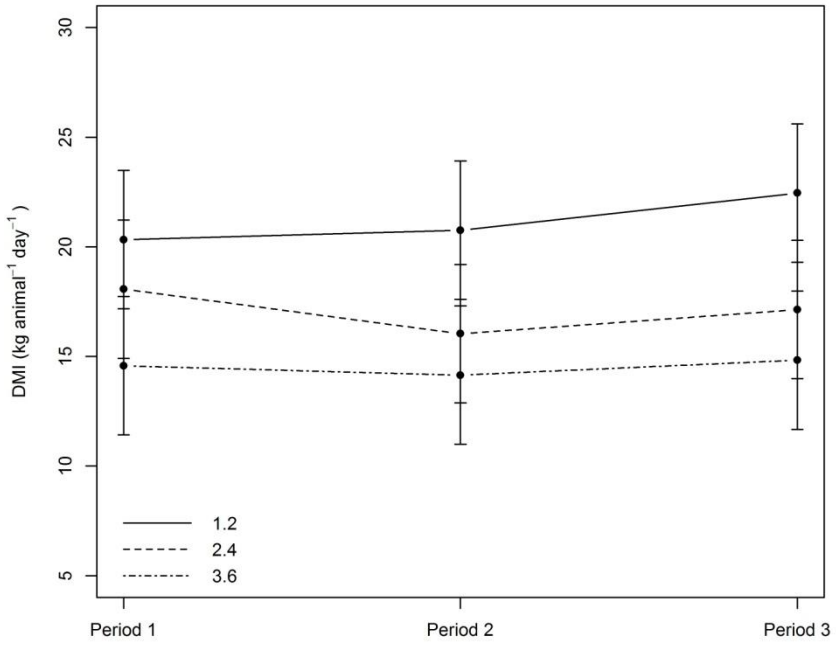


Figure 3-5. Dry matter intake (DMI) (kg animal^{-1} day^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

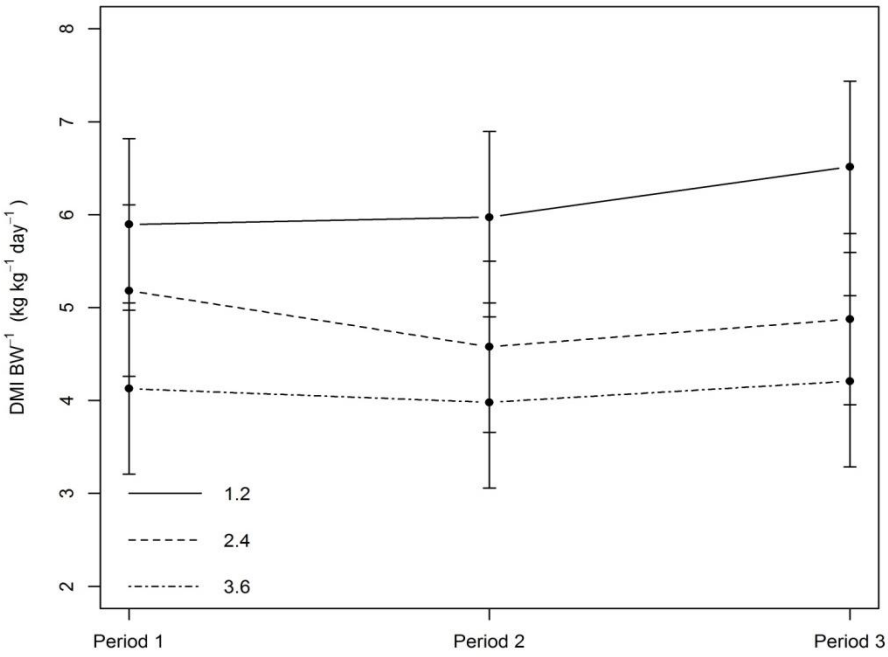


Figure 3-6. Dry matter intake (DMI) per kg body weight (BW) (kg kg^{-1} day^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

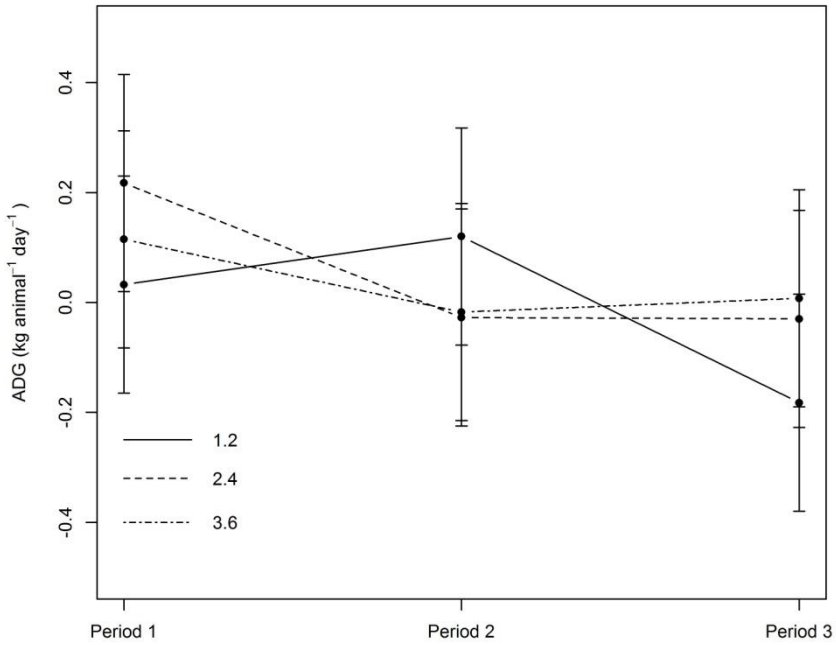


Figure 3-7. Average daily gain (ADG) (kg animal^{-1} day^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

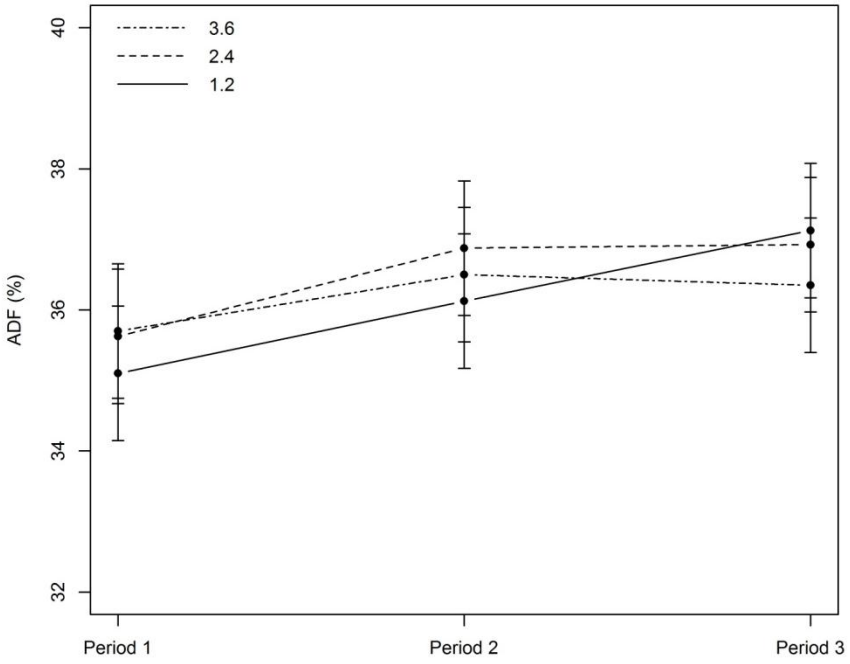


Figure 3-8. Acid detergent fiber (ADF) (%) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

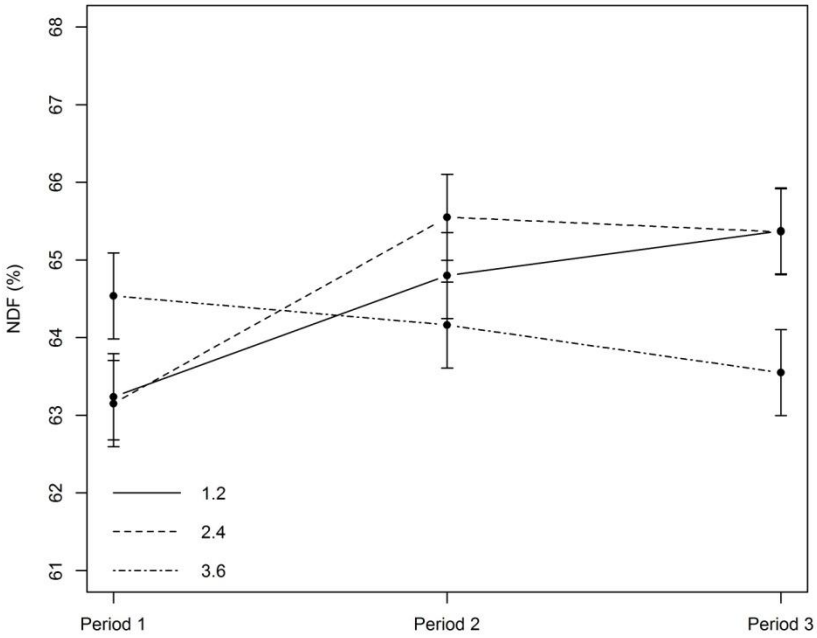


Figure 3-9. Neutral detergent fiber (NDF) (%) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

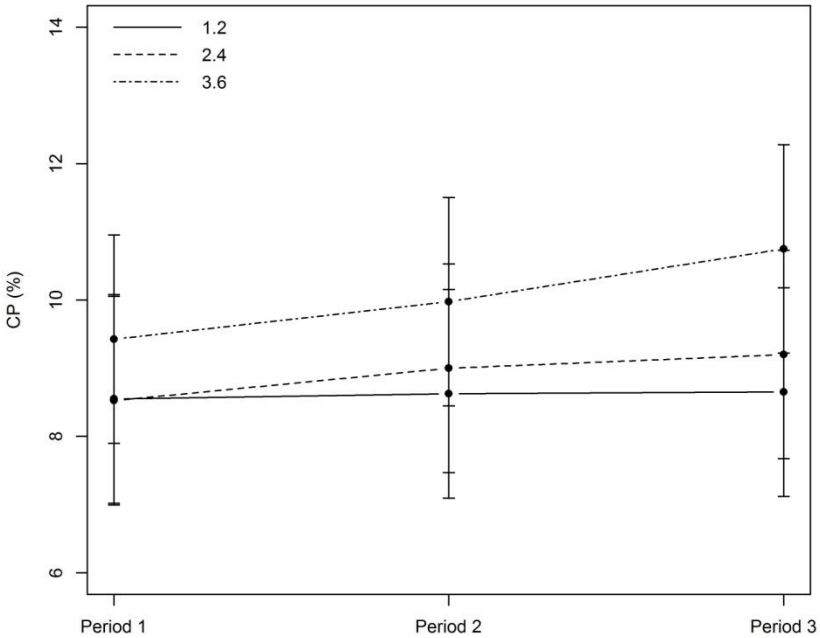


Figure 3-10. Crude protein (CP) (%) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

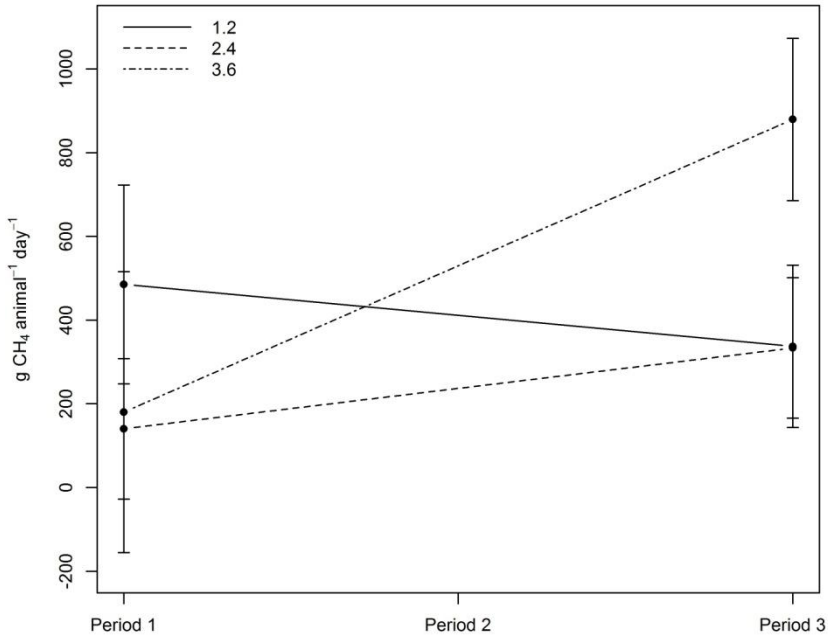


Figure 3-11. Methane production (g CH_4 $animal^{-1}$ day^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

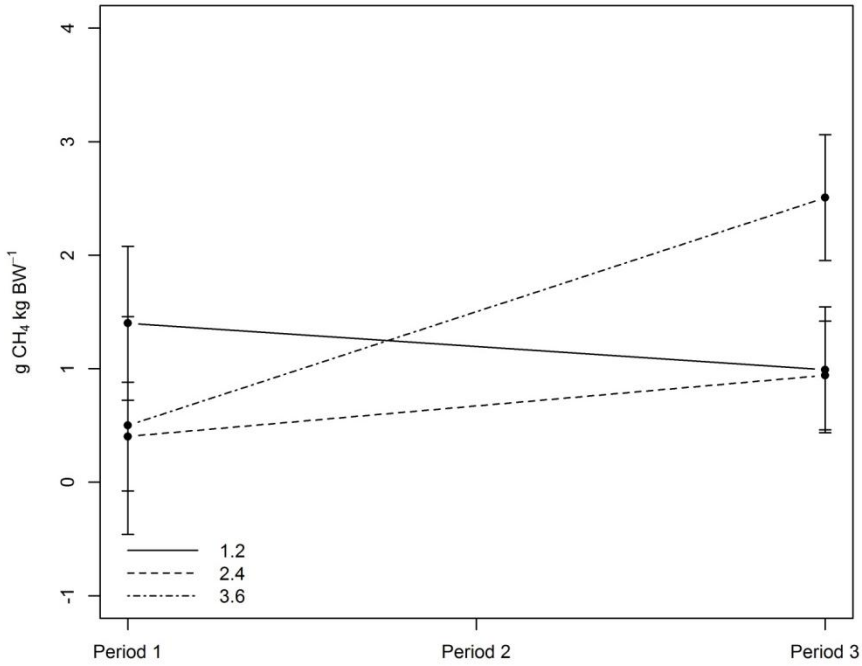


Figure 3-12. Methane production (g CH_4 kg BW^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

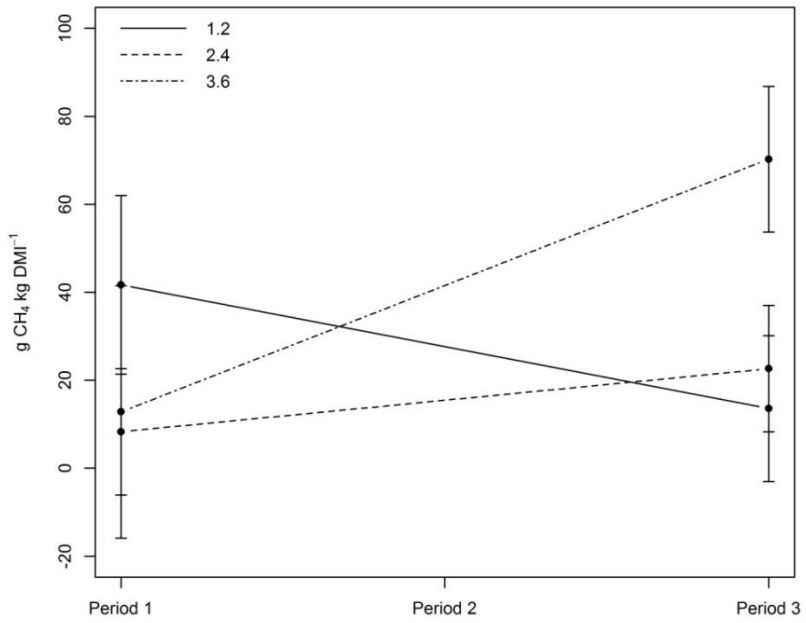


Figure 3-13. Methane production (g CH_4 kg DMI^{-1}) response to three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

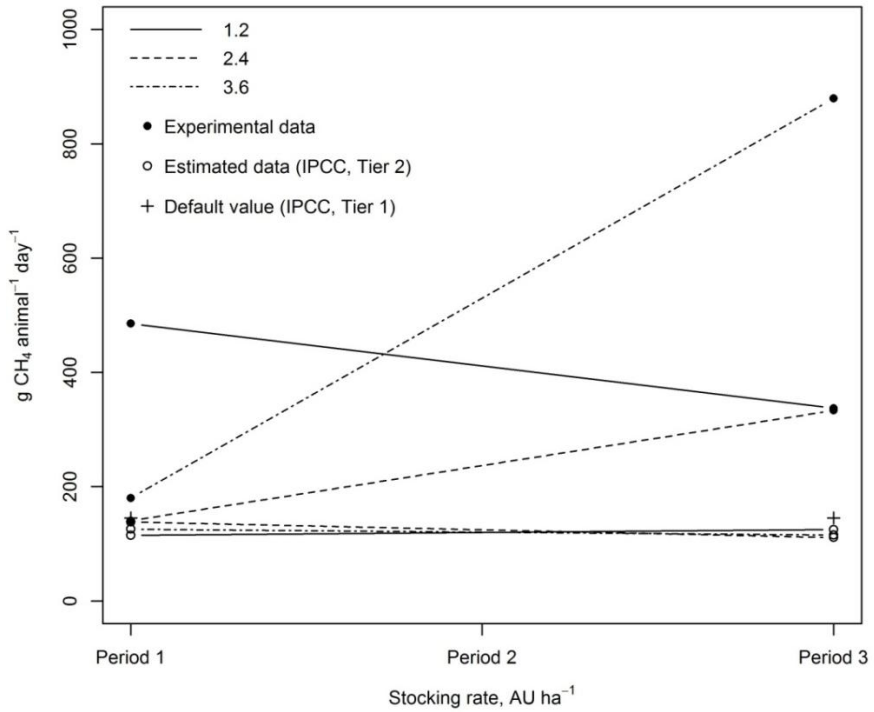


Figure 3-14. Measured and simulated methane production (g CH4 $animal^{-1}$ day^{-1}) in three stocking rates (1.2, 2.4 and 3.6 AU ha^{-1}) in 2012. The value for IPCC Tier 1 is a default value for beef cattle in the United States (IPCC, 2006), while values for IPCC Tier 2 were simulated using the IPCC's Tier 2 methodology (IPCC, 2006) using the average daily gain from Periods 1 and 3 in the field experiment presented in this chapter (Table 3-6). Period 1: June 25 to July 22; Period 2: July 23 to Aug. 19; Period 3: Aug.20 to Sep. 18.

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BIOGRAPHICAL SKETCH

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