Methane Emissions of Beef Cattle on Forages: Efficiency of Grazing Management Systems

H. Alan DeRamus,* Terry C. Clement, Dean D. Giampola, and Peter C. Dickison

ABSTRACT

Fermentation in the rumen of cattle produces methane (CH_4). Methane may play a role in global warming scenarios. The linking of grazing management strategies to more efficient beef production while reducing the CH_4 emitted by beef cattle is important. The sulfur hexafluoride (SF_6) tracer technique was used to determine the effects of best management practices (BMP) grazing compared with continuous grazing on CH_4 production in several Louisiana forages during 1996–1998. Cows and heifers (*Bos taurus*) grazed common bermudagrass [*Cynodon dactylon* (L.) Pers.], bahiagrass (*Paspalum notatum* Flugge), and ryegrass (*Lolium multiflorum* Lam.) pastures and were wintered on bahiagrass hay with supplements of protein molasses blocks (PMB), cottonseed meal and corn (CSMC), urea and corn (URC), or limited ryegrass grazing (LRG). Daily CH_4 emissions were between 89 and 180 g d^{-1} for young growing heifers and 165 to 294 g d^{-1} for mature Simbrah cows. Heifers on "ad lib" ryegrass in March and April produced only one-tenth the CH_4 per kg of gain as heifers on LRG of 1 h. Using BMP significantly reduced the emission of CH_4 per unit of animal weight gain. Management-intensive grazing (MIG) is a BMP that offers the potential for more efficient utilization of grazed forage crops via controlled rotational grazing and more efficient conversion of forage into meat and milk. Projected CH_4 annual emissions in cows reflect a 22% reduction from BMP when compared with continuous grazing in this study. With the BMP application of MIG, less methane was produced per kilogram of beef gain.

RUMINANTS in "natural" production systems are generally inefficient in converting plant biomass into animal protein. Production increases have depended on increasing animal numbers, or increasing stocking rates with little increase in individual animal production especially on the more fertile grasslands. There is a growing appreciation that the efficiency of feed utilization per unit of production of meat, milk, or work can be improved considerably by simple technology or management inputs. If applied, this could have major implications for stabilizing global atmospheric methane concentrations (Leng, 1993).

Researchers have identified management techniques that increase livestock production efficiency (Henning et al., 2001). Few studies have been done on the emission rates of methane in relation to management and productivity in grazing systems (Pavao-Zuckerman et al., 1999). Studies linking methane emissions in grazing management are needed to compare improved practices with traditional animal management. Quantification of emission rates of methane from beef cattle consuming different forages and protein supplements and grazing under different management systems will provide information to improve beef production efficiency. Relating the production efficiency for common and improved management systems for livestock producers is important in helping them to improve operations.

The methane (CH_4) produced from enteric fermentation by domesticated livestock is estimated to contribute 21% of total U.S. anthropogenic emissions of "greenhouse gas," with cattle contributing 95% of total livestock emissions (USEPA, 1993a). Methane produced by enteric fermentation in grazing cattle is of interest because it is seen as a strong contributor to various climate change scenarios associated with global warming. The possibility of limiting CH_4 emissions from beef cattle by improving grazing management systems provides economic as well as environmental benefits. The best strategy for mitigation of cattle CH_4 is probably through enhancing the efficiency of feed energy use. Assuming a constant percentage of methane loss, this strategy will decrease methane loss per unit of product and probably decrease methane emissions by cattle over the long term (Johnson and Johnson, 1995)

Methane is a by-product of the microbial fermentation of carbohydrates in the diets of ruminant animals. Because cattle can lose about 6% of their dietary intake energy as CH_4, substantial research to estimate this production and to reduce CH_4 emissions has been completed (Johnson and Johnson, 1995). Most of the data available on cattle CH_4 emissions have used information derived from calorimetry studies done with closed respiration chambers. Using these data, models and prediction equations were developed to estimate CH_4 production from ruminants with parameters such as dry matter intake and feed characteristics (Johnson and Johnson, 1995; Crutzen et al., 1986). Johnson et al. (1994) noted that these studies involved artificial environments with restricted animal movement, even though the artificial conditions may not accurately predict the CH_4 production in actual environments such as pasture or range (USEPA, 1993a). Kurihara et al. (1999), using respiration chambers, also concluded that the relationships between CH_4 production, energy utilization, and liveweight change of cattle fed on tropical forages differ from those of cattle fed on diets of temperate forages.

An alternative to calorimetry chamber estimates of CH_4 emissions from cattle is the sulfur hexafluoride (SF_6) tracer method developed at Washington State University (Johnson et al., 1994; Westberg et al., 1996). Pavao-Zuckerman et al. (1999) and McCaughey et al. (1997), using this technique, have confirmed similar CH_4

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Abbreviations: ADG, average daily gain; BMPs, best management practice; CSMC, cottonseed meal and corn; CP, crude protein; DM, dry matter; LRG, limited ryegrass grazing; MIG, management-intensive grazing; MW, metabolic weight; PMB, protein molasses block; URC, urea and corn.

emissions in grazing cattle. This tracer technology allows the monitoring of CH_4 emissions in grazing management systems and comparison of animal weight gain and total beef production per unit of land.

Recent estimates show that about one-half of the beef cows in the USA are presently located in the southern region (Texas to Florida and below the 30th parallel). Beef production in the southeastern USA has traditionally consisted mainly of cow and calf enterprises with the calves sold at weaning (Bagley, 1993). These operations have frequently revealed low profit potential. Studies have shown (Hoveland, 1986) that income from calf sales is low because the total calf production may be as low as 70 kg ha^{-1} annually. Cow–calf production systems in the southern USA are based primarily on forages. Most of these systems consist of warm-season perennial grasses, such as bermudagrass or bahiagrass, during much of the grazing season. Large amounts of forage production can occur due to the long growing season, usually more than 300 d in Louisiana. During most of that time, however, the dominant, warm-season perennial grasses, which are introduced species, lack sufficient quality for maximum sustained beef cattle weight gain. It is speculated that the genetic production potential of most cow herds is limited by the lack of, or management for, adequate amounts of high-quality forage. Average weaning weights of 150 to 200 kg for calves in many southern states show the lack of proper forage management (Bagley, 1993). In addition, these warm-season forages are harvested for hay when they are rather mature and of low quality and then subsequently fed to most beef cattle herds in Louisiana for maintenance during the winter period. The long growing season allows extensive grazing of the forage, which is a more efficient means of harvesting (Beetz, 2002). With controlled-rotation grazing management or management-intensive grazing (MIG) systems, the potential exists to maximize both forage and beef production and increase the efficiency of beef production (Henning et al., 2001; White and Wolf, 1996).

Grazing is often practiced on marginally productive lands that are not suited to crop production. Beef cattle have the ability to harvest forages of lower quality from land with no or few alternatives for other crops (Fontenot et al., 1995). Grazing management implies a degree of control over both the animals and the forage sward. Management-intensive grazing allows better utilization of grazed forage crops with short-duration grazing in small paddocks (Davis et al., 1995; Morrow et al., 1991). While the costs of fencing and watering systems can be substantial, there is the potential for greater returns in grazing enterprises.

The objectives of this project were to determine and demonstrate methods for improving beef production per unit of methane emission, and to measure the productivity of beef cattle grazing different adapted forages under traditional and improved management systems.

MATERIALS AND METHODS

Methane

Sulfur Hexafluoride Tracer Method

The Washington State University method for measuring eructated CH_4 was used in this study (Johnson and Johnson, 1995). The sulfur hexafluoride (SF_6) tracer method involves placing a small brass permeation tube, with a known permeation rate of SF_6, in the reticulum. Eructated gas samples are continuously obtained through a capillary tube connected to a collection canister placed on the neck of the animal. Pavao-Zuckerman et al. (1999) described the apparatus and collection methods of the SF_6 tracer method.

A horse halter modified with 0.127-mm-i.d. stainless steel capillary tubing and with an in-line 15-μm filter (Nupro Company, Willoughby, OH) was placed on the animal's head and connected to an evacuated sampling canister (Fig. 1). Collection canisters, constructed of PVC pipe, were attached to a vacuum pump in the laboratory to create a negative pressure of $<6.9 \times 10^3$ Pa (-0.07 atm). As the vacuum in the sampling canister was slowly dissipated, the negative pressure steadily drew the sample of air from around the mouth and nose of the animal. The duration of sampling was determined for a $>$24-h collection period by varying the length of the capillary tube. After collection of the sample and pressuring the canister with nitrogen (N), lab analysis using gas chromatography determined the CH_4 and SF_6. With a known rate of SF_6 permeation, and measured concentrations of CH_4 and SF_6 in the canister, the CH_4 emission for each animal can be calculated.

Each collection period consisted of four consecutive 24-h periods (Monday through Friday) with canisters exchanged at the same time each subsequent day. The filled canisters were transported to the laboratory for CH_4 and SF_6 analysis on a daily basis. Additional canisters were placed near the experimental pastures to monitor background levels of CH_4 and SF_6 daily during each sampling period.

In the laboratory, each canister was pressurized with N gas to about 1.242×10^5 Pa (1.2 atm) to allow auto-pressure injection into the gas chromatograph (GC) (Model SRI 8610C; SRI Instruments, Las Vegas, NV). A GC fitted with an electron capture detector (ECD) and a flame ionization detector (FID) was used to determine the concentration of CH_4 and SF_6, respectively, in the canister gas samples. The GC was calibrated with standard gases for CH_4 and SF_6. Two subsamples from each canister were processed through the GC for analysis. The CH_4 emission rate for each experimental animal was calculated as the product of the permeation tube emission rate of SF_6 and the ratio of CH_4 and SF_6 in the sample.

Following the last sampling period in 1997, the permeation tubes were removed surgically by rumenotomy from the cows and heifers. The permeation tubes used in the 1997–1998 collections were not removed from the cows, since the animals remained in the production herd. The SF_6 was completely exhausted, in accordance with the requirements of Food and Drug Administration (FDA) Investigational New Animal Drug Use (INAD) 9544.

Animals

All collection trials used Brahman crossbred females. Because of their Simbrah breeding of 5/8 Brahman and 3/8 Simmental, the cattle were well adapted to the humid conditions of the Gulf Coast region. Purchased weanling heifers born in autumn 1995 were used initially as stockers and retained for breeding and further use in subsequent years as bred heifers and lactating cows. Simbrah cows, aged 3 to 7 yr, from the University of Louisiana at Lafayette herd were used for the duration of the experiment. University herd heifers born during the autumn of 1996 were also added to this experiment in May 1997. Thus, the classes of animals used in this study included yearling heifers (stockers), first-calf heifers, and mature cows. Age, weight, frame score, and body condition score

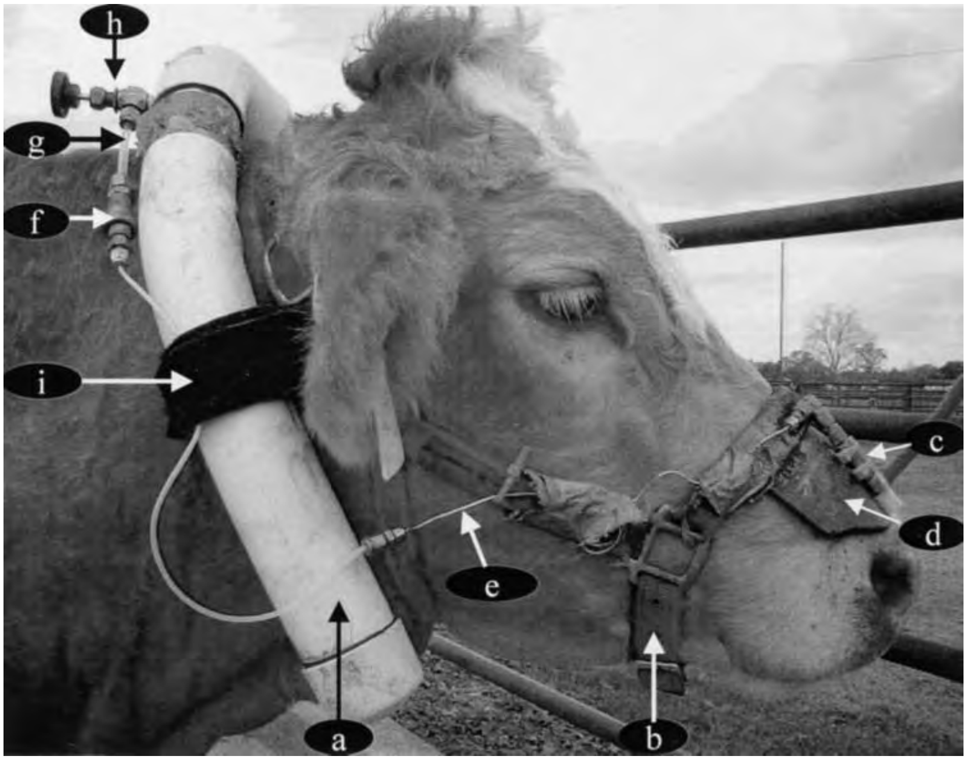

Fig. 1. Methane collection equipment as worn by a grazing cow: (*a*) collection canister; (*b*) halter; (*c*) filter inlet connected to capillary tubing; (*d*) leather muzzle protector; (*e*) stainless steel capillary tubing attached to halter; (*f*) quick-connect coupling of tubing to canister; (*g*) Teflon tubing between shut-off valve and quick-connect to capillary tubing; (*h*) shut-off valve on canister; (*i*) Velcro strip to anchor canister to halter.

were recorded and used as a basis for blocking and allotment to the treatment and control herds.

All cattle used in this study were raised and maintained under the same conditions used in commercial beef cattle production in the area. The cattle required extensive halter breaking, gentling, and training to stand tied for this research project because they had only been handled during routine breeding, deworming, and vaccination. The training period included the use of halters and Velcro-attached "dummy" canisters on the cattle to acclimate them to the CH_4 collection apparatus. The cows were not pregnant and were implanted with Syncro-Mate B (Sanofi Animal Health, Overland Park, KS) for estrus control because it was noted that cycling cows damaged the collection apparatus. The cows were placed in an autumn calving program to accommodate as many collections as possible during the grazing season and still evaluate a typical production system.

In October 1996, both cows and heifers were blocked on weight and age at the beginning of the experiment and assigned to either the treatment or control group as discussed below. "Tester" animals in each of the two experimental herds included six yearling heifers with an average weight of 390 kg and six cows with an average weight of 540 kg that had nursing calves. Methane measurements were obtained from these "tester" animals in each herd. In 1997, six weanling heifers were added to each herd so that yearling, two-year-old, and mature cows were all included as "tester" animals.

All animals were weighed before each CH_4 collection period and when changing forage types. Body condition scores on a nine-point scale (Herd and Sprott, 1986) were recorded semiannually (in the early spring, following the winter period and in the late autumn, after the summer growing season).

Initial data collection on reproductive efficiency began in 1998. The reproductive status of all animals in the CH_4 study was synchronized to produce an autumn calving season between 15 September and 15 December. Reproductive efficiency was recorded by calving interval. Adjusted weaning weight of calves, kilogram of calf produced per cow exposed, and CH_4 emission per unit of beef produced were recorded to measure system production efficiency.

Mature cows and yearling heifers were naturally mated to Angus bulls from 15 December through 15 March. Two herd bulls rotated between the two herds every 21 d.

Forages

Pastures located on the University of Louisiana at Lafayette Farm (30°5.3′ N, 91°53.0′ W) were used in this study. All pastures were on Memphis silt loam soil (fine-silty, mixed, active, thermic Typic Hapludalf) with a 3 to 5% slope. Pasture treatments included:

(i) Control: unimproved pasture with continuous stocking of naturalized revegetated cropland (typical of the area). Multiple species of forages were represented in these pastures. The base forages were warm-season perennials such as bermudagrass and bahiagrass in combination with numerous forbes. Pastures were routinely grazed with continuous stocking during a grazing season with available dry matter (DM) of 500 to 1000 kg ha^{-1}. *Continuous stocking* is defined as the continuous, unrestricted grazing of a specific pasture by livestock throughout a year or grazing season (Forage and Grazing Terminology Committee, 1992).

(ii) Treatment: well-managed, warm-season perennial pastures of bahiagrass or common bermudagrass, and overseeded with annual ryegrass for use during the appropriate growing season, using best management practices (BMP) with management-intensive grazing (MIG).

Each paddock of bahiagrass or bermudagrass was overseeded with ryegrass in September for winter grazing. Phosphorus and potassium were applied in the autumn to maintain a medium soil test level of fertility. The warm-season pastures in BMP received 50 kg N ha^{-1} as ammonium nitrate in split applications during the growing season. Ryegrass received 40 kg N ha^{-1} as urea in January and again in March.

Twenty-four paddocks of approximately 0.5 ha each in the BMP area were used with MIG with a stocking density of 50 to 60 animal units ha^{-1} d^{-1}. An appropriate recovery time of 15 to 30 d between each grazing period produced 1000 to 2000 kg of DM forage ha^{-1}. This stocking density allowed the maintenance of forage with at least 500 kg of DM ha^{-1} residue in each grazed paddock.

The unimproved pasture (control) was grazed with continuous stocking throughout the growing season (March–October) with a herd stocking rate sufficient to maintain at least 500 kg ha^{-1} of available DM forage as confirmed by monthly small plot clipping. The grazing management was established to provide sufficient forage to allow an adequate voluntary intake by the cattle.

Bahiagrass hay was used as necessary during the winter (November–March) as a maintenance diet. Hay and various protein supplements were used for the two herds. Protein supplements included: (i) cottonseed meal and corn (CSMC) to make a 14% crude protein (CP) mixture, (ii) urea and corn mixture (URC), 14% CP, (iii) protein–molasses block (PMB), and (iv) limited ryegrass (LRG) grazing when available.

Forage samples were collected from each sward before and after each grazing period to determine quantity available at that physiological state of development and residual forage to calculate forage utilization. Forage production on each pasture being grazed was measured with quadrats to determine the total quantity available.

Forage samples were analyzed for quality components of CP and acid detergent fiber (ADF) at the Louisiana State University Forage Lab to calculate the total digestible nutrients. Fecal samples from each collection were analyzed at the Texas A&M Grazing Animal Nutrition Laboratory for prediction of digestible organic matter (DOM) and the calculation of dry matter intake. Lyons et al. (1993) used near infrared spectrum (NIRS) technology to successfully predict dietary CP and DOM of free-ranging animals. Fecal data collected in this study were used to calculate forage intake from CP and DOM with NUTBAL software developed at the Grazing Animal Nutrition Lab, Texas A&M University, by Stuth and associates (Lyons and Stuth, 1992).

Management

The control herd was managed under conditions similar to those that most producers in Louisiana practice. The control herd was maintained on the same pasture (continuous stocking) at a stocking rate of two cows per hectare. Forage was sometimes limiting when weather conditions were not favorable for adequate forage growth. Also, the control herd was maintained or "wintered" with limited supplementation that caused weight loss of about 20% of precalving weight during the period. Ryegrass was available for limit grazing of 1 or 4 h daily.

The BMP pastures were periodically fertilized to maintain a medium level of soil fertility and the animals were managed intensively with *periods of stay* of 1 to 3 d in each paddock to obtain the highest quality forage available. The warm-season perennial grasses were more tolerant of traffic and the quality difference usually did not justify a paddock shift on a daily basis. Ryegrass, however, being a more upright-growing grass and very high quality, when grazed, had animal rotation with paddock shifts at least daily. Routine health care of annual vaccination and parasite control was practiced on both herds. All animals were weighed before each CH_4 collection and when changing forage types.

When forage growth of a species was adequate (as determined by quadrat sampling of at least 1500 kg ha^{-1}) and animals were adjusted to that particular forage, two classes of cattle (both heifers and cows) at a time were used to obtain CH_4 emission during each measurement period. Cattle grazed the same forage as the one to be sampled for a minimum of two weeks before the initial sampling period to assure adequate time for rumen microorganism adaptation. Portable corral panels were constructed within the grazing paddock area to simplify daily sampling of the CH_4 collection canisters on each animal. At least five animals of the six "tester" animals available for each class were used for each measurement trial. Daily rotation on the treatment paddocks (BMP) was compared with continuous stocking on unimproved pastures (control).

Methane Collections and Forage Type

Methane data collection began in October 1996 with the cows and the 1995 heifers on warm-season perennials. Collections and forage types were: bahiagrass, bermudagrass, bahiagrass hay with either PMB, CSMC, URC, or LRG vs. ad lib ryegrass. In May 1997, new heifers (1996 autumn-born) grazed warm season forage along with the cows that had undergone rumenotomy for permeation tube removal. Collections were made with the new set of weanling heifers and dry cows in the summer of 1997. Collections continued on bahiagrass and bermudagrass with heifers and cows in autumn of 1997 and summer of 1998. Collections on ryegrass were made with the yearling heifers during February to April 1998. Limited grazing time of 1 or 4 h daily on ryegrass was also used as a protein supplement during February and March for the cows. The mature and 2-yr-old cows were supplemented with CSMC or URC during February and March of 1998. Collections were made with the yearling heifers on bermudagrass in August and September of 1998.

Methane collections with original cows on the project were suspended in early 1997 for rumenotomy in May with removal of the original permeation tubes. New permeation tubes were deposited into the cows in July. Collections were resumed on summer forage and then subsequently on the hay and protein supplement wintering diets. Daily emissions per animal were combined within each CH_4 sampling period and calculated on an hourly, daily, and annual basis for each forage type. Methane emissions were expressed per unit of metabolic weight (MW = kg of body weight$^{0.75}$), and per kilogram of animal weight gain. Expressing CH_4 emissions per unit of MW factored the size of the animal into the emission rate, since body mass has been related to energy expenditure (Ferrell, 1988). Kurihara et al. (1999) noted that CH_4 production per unit of animal production (i.e., g kg^{-1} live-weight gain) is a suitable index for comparing greenhouse emissions of livestock under different feeding regimens. Since the expression of CH_4 emissions per unit of average daily gain (ADG) considers the CH_4 emission per unit of animal performance, it provides a measure of efficiency.

Statistical Analysis

The data were analyzed with the general linear model (GLM) procedure of SAS (SAS Institute, 1995). The experimental design used was a randomized complete block design.

Table 1. Means for methane (CH_4) emission estimates and performance in cows and heifers on bahiagrass pastures in 1996 and 1997.

	Fall 1996		Spring 1997		Summer 1997		
	Continuous	BMP†	Continuous	BMP	Continuous	BMP	LSD (0.05)
				Cows			
Initial weight, kg	573	572	586	582	601	595	NS‡
ADG§, kg	−0.33c¶	0.22b	0.91a	0.85a	0.40b	0.31b	0.12
Methane							
$g\ d^{-1}$	217b	181c	174c	120d	249a	223b	19
$g\ kg^{-0.75}\ d^{-1}$#	1.85b	1.55c	1.44c	1.01d	2.04a	1.85b	0.14
				Heifers			
Initial weight, kg	400a	379a	303b	295b	310b	311b	50
ADG, kg	−0.45d	−0.46d	0.62ab	0.75a	0.43bc	0.51b	0.17
Methane							
$g\ d^{-1}$	166a	114b	94c	86c	131b	124b	19
$g\ kg^{-0.75}\ d^{-1}$	1.86a	1.33c	1.29c	1.21c	1.77ab	1.67b	0.14

† Best management practices grazing system.
‡ Not significant.
§ Average daily gain.
¶ Means within a row followed by same letter are not significantly different ($P < 0.05$).
# The unit $g\ kg^{-0.75}$ is the metabolic weight of cattle.

Blocks were the replication of the experiment at different collection periods on various forages. Data for each forage type were analyzed by analysis of variance using the model:

$$Y_{ijkl} = \mu + P_i + C_j + T_k + (CT)_{kl} + A(CT)_{l(jk)} + \varepsilon_{ijkl}$$

where Y = initial weight, ADG, or CH_4 and P = collection period, T = pasture grazing management system (BMP or continuous), C = animal class (weanling heifer, first-calf heifer, mature cow), and A = animal identification. Mean comparisons were made for each variable using least significant differences (LSD, $P < 0.05$). Day-to-day measurements of individual animals were nested within the interaction of grazing management system and animal class.

RESULTS AND DISCUSSION

Methane emissions in this study showed considerable variation among different classes of animals, different seasons of the year, and on different forages. Daily emissions of 86 to 193 g of CH_4 (Tables 1 and 2) from heifers and 120 to 255 g CH_4 d^{-1} from cows were within the range of total CH_4 emissions as reported by others using the SF_6 tracer method (173–219 g CH_4 d^{-1} from steers, McCaughey et al., 1997; and 150–240 CH_4 d^{-1} from steers and cows, Pavao-Zuckerman et al., 1999). Using prediction equation data, Crutzen et al. (1986) estimated that the total annual CH_4 production from cattle on range in the USA would be about 54 kg per animal. The ranges of annual CH_4 if calculated from the ranges of daily emissions reported in this study would be between 32 and 83 kg per heifer and between 60 and 95 kg per cow. However, the BMP system always had significant effects (Tables 1 and 2) on the amount of CH_4 that cows emitted with BMP being lower than the continuous grazing. No significant differences were observed in the heifers during the spring and summer of 1997 on either bermudagrass or bahiagrass.

Kurihara et al. (1999) observed that CH_4 production was higher on tropical forage diets than published values for temperate forage diets. This higher methane conversion rate (MCR) of tropical forage species is presumably related to the relatively high levels of fiber and lignin, low levels of nonfiber carbohydrate (Van Soest, 1994), and low digestibility (Minson, 1990) compared with temperate forage species. Kurihara et al. (1999) also suggested that tropical forage species might have higher MCR than temperate forage diets.

The average body condition scores for cows in both management systems varied between 4 and 7 (on a scale

Table 2. Means for methane (CH_4) emission estimates and performance in cows and heifers on bermudagrass pastures in 1996, 1997, and 1998.

	Fall 1996		Summer 1997		Fall 1997		Summer 1998		
	Continuous	BMP†	Continuous	BMP	Continuous	BMP	Continuous	BMP	LSD (0.05)
					Cows				
Initial weight, kg	560b‡	551b	614a	600a	631a	621a			32
ADG§, kg	0.34c	0.50b	0.55b	0.66a	0.21d	0.38c			0.11
Methane									
$g\ d^{-1}$	255a	219b	226b	179c	249a	225b			18
$g\ kg^{-0.75}\ d^{-1}$¶	2.22a	1.93b	1.83bc	1.48d	1.98b	1.81c			0.17
					Heifers				
Initial weight, kg	390b	368b	327c	323c	341c	343c	470a	482a	24
ADG, kg	0.11e	0.29d	0.44c	0.61ab	0.21d	0.31d	0.55b	0.68a	0.13
Methane									
$g\ d^{-1}$	193a	143bc	138c	129c	166b	160b	189a	157b	18
$g\ kg^{-0.75}\ d^{-1}$	2.20a	1.70c	1.79c	1.69cd	2.09ab	2.01b	1.87bc	1.53d	0.17

† Best management practices grazing system.
‡ Means within a row followed by same letter are not significantly different ($P < 0.05$).
§ Average daily gain.
¶ The unit $g\ kg^{-0.75}$ is the metabolic weight of cattle.

of 1 to 9) when recorded biannually. These scores indicated that cows were generally in acceptable condition.

On bahiagrass (Table 1), the BMP cows gained weight (ADG) while the control cows lost weight during the September to October (fall 1996) collection. All heifers lost weight. Differences were observed in weight gain between seasons in cows but there were no other significant differences among the treatments for weight gain on bahiagrass. All groups had less DM intake in the fall collection than required to support production above maintenance. The warm-season forages of bahiagrass and bermudagrass in summer and autumn did not support high weight gain or efficient beef production. Forage quality of bahiagrass (crude protein < 70 g kg^{-1} and in vitro organic matter digestibility [IVOMD] < 500 g kg^{-1}) usually limits animal performance in the latter part of the summer and into the fall (DeRouen et al., 1993). When forage quality is low, a low stocking density and continuous stocking allow the animals to select portions of the forage plant that are higher in quality. On bahiagrass, the control cows gained slightly more weight in spring (0.91 vs. 0.85 kg d^{-1}) and summer (0.44 vs. 0.31 kg^{-1}) than the BMP cows (Table 1). Continuous stocking allows maximum selective grazing, which frequently results in higher per animal responses than from rotational stocking (Matches and Burns, 1995). This advantage for continuous stocking was observed with both cow and heifer weight changes on bahiagrass or bermudagrass in the July to October 1997 collections (Tables 1 and 2).

Daily CH_4 emissions ranged from 120 to 249 g d^{-1} for cows and 86 to 166 g d^{-1} for heifers grazing on bahiagrass (Table 1). The emissions were lower in the spring when forage quality was higher than in summer and fall with forage quality declining. There was variation between seasons, when CH_4 emissions are expressed per unit of MW, but the BMP grazing management system produced significantly less CH_4 at each collection. The calculated annual rate of CH_4 emission on bahiagrass of 45 to 97 kg for cows and 34 to 61 kg for heifers is well within the range of reported values (Johnson et al., 1994; Pavao-Zuckerman et al., 1999).

The CH_4 emissions on bermudagrass varied between seasons with both cows and heifers emitting less CH_4 in summer of 1997 than in either fall collection. Both cows and heifers emitted less CH_4 on BMP than on continuous bermudagrass pastures (Table 2). The quality of the forage is also reflected in the production observed on the bermudagrass. Average daily gain was higher in summer than in autumn for both cows and young heifers (Table 2), and ADG was higher on BMP pasture than on continuous grazing. Both cows and heifers had higher ADG on the bermudagrass BMP pastures. Forage intake is a function of forage quality in that as quality increases, the intake also increases. Missouri workers (Davis et al., 1995; Morrow et al., 1991) noted that as the grazing period is lengthened, forage quality is likely to be lower in those paddocks grazed for longer periods. This also leads to a reduced intake, particularly during the latter days of the grazing period.

The CH_4 emissions of the growing yearling heifers on ryegrass (Table 3) were significantly different at each collection. One-hour grazing time on ryegrass was adequate as a protein supplement but was not sufficient to support the genetic potential production (weight gain) of these heifers. The beef weight gains of the 4-h and ad lib treatments confirmed that high-quality forage can support excellent rates of gain. These stocker heifers gained 1.26 kg daily on ad lib, 0.71 kg daily on 4-h, and only 0.12 kg daily on 1-h grazing of ryegrass. Cool-season annuals can greatly extend the forage grazing season by providing an excellent-quality forage capable of producing gains of 1.0 kg d^{-1} (Hoveland et al., 1978; Bagley et al., 1988; Mooso et al., 1990). These weight gains on ryegrass also show increased efficiency of CH_4 emission with increased grazing time. When the CH_4 emissions are expressed as CH_4 produced per kg of weight gain, the higher rates of gain are certainly more efficient. Methane emissions per kg of ADG were only 20 to 30 g on ad lib ryegrass that supported 1.1 kg ADG during the spring season. Forage quality as measured by in vitro organic matter digestibility (not shown) declined from a digestibility in the high 70s in February to the mid 60s in April; the CH_4 emission per unit of gain increased for similar amounts of grazing time (47 to 64 g kg^{-1} d^{-1} for ad lib and 133 to 213 g kg^{-1} d^{-1} for 4 h; Table 3). With the high-quality ryegrass forage, the additional grazing time was critical to achieve adequate dry matter intake for these stocker animals. The higher weight gain resulted in increased efficiency of beef pro-

Table 3. Means for methane (CH_4) emission estimates, forage dry matter (DM) intake, and performance in heifers on ryegrass pastures in 1998.

	February		March		April			Average	
	Grazing time (h d^{-1})								
	1 h	4 h	4 h	ad lib	4 h	ad lib	LSD (0.05)	4 h	ad lib
Initial weight, kg	340c†	341c	351bc	372b	381b	415a	31		
ADG‡, kg	0.12c	0.42b	1.11a	1.31a	0.61b	1.20a	0.29	0.78	1.26
kg DM intake, total	7.82c	8.73b	9.86a	9.27ab	9.82a	9.91a	0.81		
Ryegrass	2.55	4.68	8.64	9.27	5.73	9.91			
Hay	5.27	4.05	1.22	–	4.09	–			
Methane									
g d^{-1}	140b	125bc	148b	135b	130bc	176a	16	137	164
g kg$^{-0.75}$ d^{-1}§	1.76b	1.58c	1.83b	1.59c	1.51c	1.91a	0.07	1.63	1.75
g kg^{-1} gain d^{-1}	1167a	298b	133c	103c	213bc	147c	119	214	125

† Means within a row followed by same letter are not significantly different ($P < 0.05$).
‡ Average daily gain.
§ The unit g kg$^{-0.75}$ is the metabolic weight of cattle.

duction with less CH_4 being emitted per unit of gain on ad lib ryegrass. When compared with the 1-h grazing, the ad lib ryegrass produced approximately one-tenth the CH_4 per kg of beef weight gain.

Similar results of CH_4 emissions (Table 4) of 1.51 to 2.34 g of CH_4 per unit of MW were obtained in 1998 as 1997 with the protein supplements fed as wintering diets to the mature cows. Methane emissions on all the protein supplements were significantly greater than that observed on the ad lib ryegrass. The differences observed between the protein supplement diets on bahiagrass hay reflected the quality of the hay with greater CH_4 emissions on the lower-digestibility hay. The laboratory analyses of the hay (not shown) indicated that hay alone was not sufficient for maintenance of these cows.

The protein supplement comparisons were continued in 1998 with the two management levels of feeding with each of the protein supplements. The two management systems were planned to allow the BMP herd to maintain or gain body weight of at least 0.5 kg d^{-1} gain and positive condition scores while the control level of feeding was designed below maintenance to allow a slight weight loss. Early-season limit grazing (1 or 4 h) of ryegrass (LRG) resulted in less CH_4 emission (1.5 and 2.0 g MW^{-1}) than other protein supplements. However, during late-season grazing (late April) LRG produced the highest CH_4 emissions recorded (2.46 g MW^{-1}). With higher forage intakes, more CH_4 was produced. Within each protein supplement, the higher feeding levels produced significantly more CH_4.

Development of "environment-friendly" livestock production systems demands that the increased production be met by increased efficiency of production and not through increased animal numbers (Leng, 1993). Annual CH_4 emissions from the BMP in this study reflect a reduction of 22% (Fig. 2) when projected with the higher values obtained from the control or continuous grazing system. This figure is a prediction graph using daily CH_4 emission values selected from data of the two management systems represented in this study. By selecting the forage system each month that resulted in the least CH_4 emissions, these mature cows would emit 67.5 kg CH_4 annually vs. 86 kg CH_4 for the continuous grazing and wintering system with the most CH_4 emissions.

Methane emissions are a function of the size of the animal population, the quantity of feed consumed, and the efficiency by which an animal converts feed to product. With a greater amount of CH_4 emitted the efficiency is lower. Improving animal productivity decreases CH_4 emissions per unit of product. At the basic level, feed goes to maintenance and product. Maintenance is the proportion of feed needed to satisfy the basic metabolic requirements that keep the animal alive. A significant fraction of the CH_4 emitted by cattle (40–60%) comes from the proportion of feed used for maintenance (USEPA, 1993b).

Reproductive Efficiency

The reproductive status of all animals in the CH_4 study was synchronized to produce a fall calving season

Table 4. Means of methane (CH_4) emission estimates and animal performance with bahiagrass hay and various protein supplements in cows and heifers in 1997 and 1998.

	1997						
	Bahia hay	Bahia hay + 1.1 kg PMB†	Bahia hay + 2.2 kg CSMC‡	Bahia hay + 2.2 kg URC§	Bahia hay + LRG¶, 2 h	Ad lib ryegrass	LSD (0.05)
Cows							
Initial weight, kg	523b#	585a	607a	595a	605a	614a	32
ADG††, kg d^{-1}	−0.13c	0.82b	0.91b	0.91b	0.86b	1.41a	0.29
Methane							
g d^{-1}	221c	238b	262a	251a	263a	230bc	14
g $kg^{-0.75}$ d^{-1}‡‡	2.02ab	2.00ab	2.14a	2.08c	2.16a	1.87b	0.16
Heifers							
Initial weight, kg	400b	370b	448a	440a	445a	445a	37
ADG, kg	−0.05c	0.59b	0.55b	0.73b	0.68b	1.36a	0.38
Methane							
g d^{-1}	228a	210b	206b	194b	200b	167c	16
g $kg^{-0.75}$ d^{-1}	2.15a	2.09a	2.12a	2.02a	2.06a	1.72b	0.19

	1998								
	Bahia hay + LRG, February		Bahia hay +		Bahia hay +		Bahia hay + LRG, 4 h, April	Ad lib ryegrass	LSD (0.05)
	1 h	4 h	1.6 kg CSMC	2.5 kg CSMC	1.6 kg UR	2.5 kg UR			
Cows									
Initial weight, kg	541a	550a	534ab	566a	508b	558a	526b	565a	30
ADG††, kg d^{-1}	0.14c	0.55b	0.41b	0.91a	0.43b	0.73a	0.73a	0.91a	0.21
Methane									
g d^{-1}	165e	226c	200d	254b	196d	260b	294a	272b	19
g $kg^{-0.75}$ d^{-1}‡‡	1.51f	2.0cd	1.82d	2.08c	1.77de	2.26bc	2.46a	2.34ab	0.19
Heifers									

† Protein molasses block.
‡ Cottonseed meal and corn mixture (14% crude protein).
§ Urea and corn mixture (14% crude protein).
¶ Limited ryegrass grazing.
\# Means for the same variable in a row within a year followed by same letter are not significantly different ($P < 0.05$).
†† Average daily gain.
‡‡ The unit g $kg^{-0.75}$ is the metabolic weight of cattle.

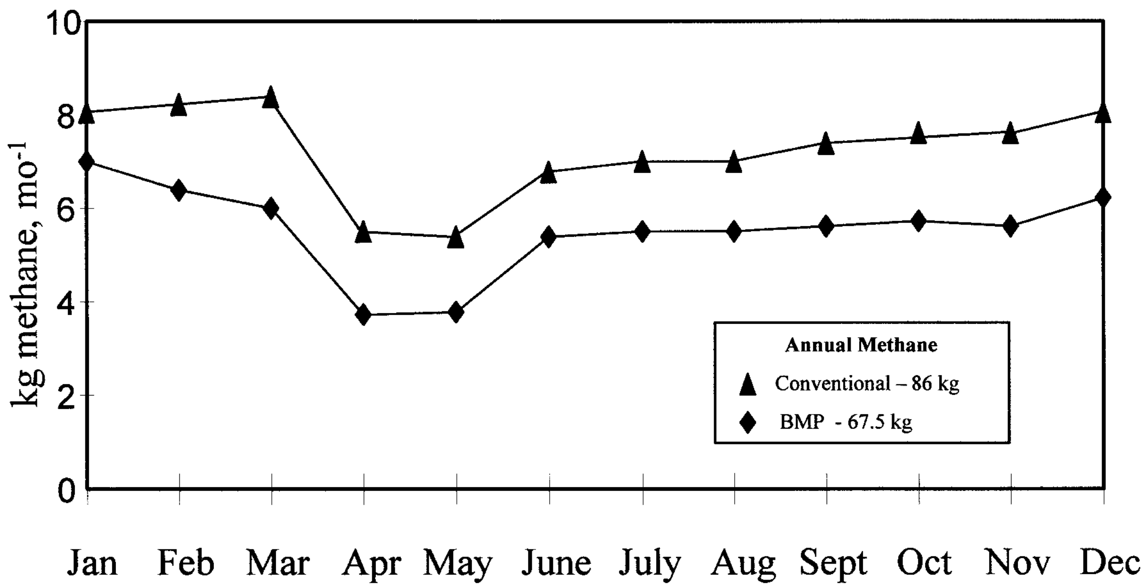

Fig. 2. Monthly methane emission projections in beef cows on best management practices (BMP) and conventional forage management systems.

between 15 September and 15 December. Reproductive efficiency was measured by calving interval, adjusted weaning weights, kg of calf produced per cow exposed, and CH_4 emissions per unit of beef produced.

Females in the two management systems were naturally mated to Angus bulls from 15 Dec. 1997 through 15 Mar. 1998. Pregnancy rates established via rectal palpation showed that the average days pregnant for mature BMP cows were 146.5, as compared with 111.5 d for the control group. The plane of nutrition in the BMP herd was sufficient to support earlier cycling and thus earlier pregnancy and calving dates. This data reflected a 21% advantage in the calving interval for the BMP treatment cows.

Weaning weights on all calves born in the autumn of 1997 were collected and adjusted according to age of the dam and sex of the offspring. The BMP group was 29 kg heavier than the control animals with a 13% advantage in weaning weight efficiency. Total forage was affected by a relatively mild winter and a severe spring drought that certainly could have affected pregnancy rates and weaning weights for both groups.

CONCLUSIONS

The CH_4 produced by enteric fermentation from grazing cattle accounts for a significant proportion of the anthropogenic CH_4. As ruminants, cattle have a relatively high maintenance requirement associated with rumen fermentation. Therefore, CH_4 emissions for maintenance cannot be modified through management strategies. Emissions of CH_4 beyond those associated with maintenance can be reduced based on the level of productivity of the animal. Consequently, implementing proper grazing management practices to improve the quality of pastures increases animal productivity and has a significant effect on reducing CH_4 emission from fermentation in the rumen. Enhancing the level of productivity decreases the maintenance subsidy and, thus, decreases the obligatory CH_4 emissions from fermentation of the feed associated with animal maintenance.

Management-intensive grazing (MIG) is an effective form of grazing BMP. Advantages of MIG may include more uniform grazing, better stand maintenance of some plant species, greater animal production per hectare, and increased opportunity for heavy grazing pressures without permanent damage to plants (Chestnut et al., 1992; Vallentine, 1990). This management leads to vigorous plant growth, healthy soil, and a more constant, nutritious diet for the cattle. Overall beef production efficiency increases and as a result the CH_4 emissions per unit of product as well as total CH_4 emissions into the atmosphere are reduced.

As we gain a better understanding of how grazing management strategies affect livestock responses in a whole-system context, we can increase the efficiency of the forage production system and reduce climate damage. We will also maintain better control of the plant and soil resource while increasing beef production efficiency.

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