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Methane emissions of beef cattle grazing tall fescue pastures

Mitchell Adam Zuckerman

To the Graduate Council:

I am submitting herewith a thesis written by Mitchell Adam Zuckerman entitled "Methane emissions of beef cattle grazing tall fescue pastures." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant, Soil and Environmental Sciences.

Henry Fribourg, Major Professor

We have read this thesis and recommend its acceptance:

John Walker, Cliff Amundsen

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

METHANE EMISSIONS OF BEEF CATTLE GRAZING TALL FESCUE PASTURES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Mitchell Adam Zuckerman

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ABSTRACT

Methane (CH_4) produced by fermentation in cattle rumens is of interest because it represents an energetic inefficiency of fermentation and because of the role CH_4 is suspected of playing in global warming scenarios. Tall fescue (*Festuca arundinacea* Schreb.) is an important forage in the eastern United States. The toxic syndrome associated with infection by the endophytic fungus *Neotyphodium coenophialum* (Morgan-Jones & Gams) Glenn, Bacon & Hanlin comb. nov. (E+), can be mitigated with management strategies which improve the forage quality of E+ tall fescue pastures. The sulfur hexafluoride (SF_6) tracer technique was used to determine the effects of tall fescue pasture management on consequential CH_4 production in spring and summer 1997 and winter and spring 1998. Two steers on each of two pastures of E+ tall fescue, endophyte free (E-) tall fescue, E+/E- strips, and E+/clover, and four steers and four cows grazing an unimproved pasture (UP) and a best management practices (BMP) pasture were used to collect eructated CH_4 samples. Average daily gains for the summer 1997 season were lower for steers grazing the E+, E-, and E+/E- tall fescue pastures (0.49 - 0.54 kg_*d^{-1}) than for those grazing the E+ tall fescue/clover pastures (0.75 kg_*d^{-1}). Daily CH_4 emissions were between about 100 - 200 g_*d^{-1} for steers and between about 150 - 240 g_*d^{-1} for cows. When data from both years were combined, steers grazing the E+ tall fescue/clover pastures emitted 18 to 20 percent less CH_4 as a function of ADG (252 $g_*kg^{-1}{}_*d^{-1}$) than steers grazing the other three pasture systems (309 - 326 $g_*kg^{-1}{}_*d^{-1}$) in the

summer. Cows emitted more CH_4 as a function of ADG (413 - 702 $g{*}kg^{-1}{*}d^{-1}$) than steers grazing the UP and BMP pastures (231 - 342 $g{*}kg^{-1}{*}d^{-1}$). This study represents the first estimation of CH_4 emissions from cattle grazing tall fescue pastures in Tennessee. The improved management practices pastures were considered to be more efficient, since less CH_4 was emitted per unit of animal performance.

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I. LITERATURE REVIEW

Methane and climate forcing

Methane (CH_4) is a greenhouse gas, meaning that it absorbs solar radiation and re-emits infrared radiation and thereby warms the earth (IPCC, 1990). Atmospheric CH_4 concentrations have been reported as increasing by about 1 percent per year (Shine et al., 1990) and to have doubled in the past 200 years (Watson et al., 1990). Increasing atmospheric concentrations of CH_4, coupled with the global warming potential (GWP) of CH_4 (21 carbon dioxide [CO_2] equivalents) show the significant role that CH_4 will play in the predicted climate forcing or, as it is more commonly known, global warming (Shine et al., 1990). The GWP indicates the relative radiative and potential climate effect attributed to 1 kg of a gas, relative to 1 kg of CO_2, by taking into account differences in atmospheric residency times (IPCC, 1990).

Atmospheric CH_4 is derived from a variety of sources. Roughly 70 percent of annual CH_4 emissions are from anthropogenic sources, while 30 percent of the annual emissions are from natural sources (U.S. EPA, 1993b). Natural sources of CH_4 emissions include wetlands, termites, and oceans (Crutzen, 1991; Watson et al., 1990). Increasing terrestrial CH_4 emissions are believed to be the result of increasing human populations and hence may be attributed to an increase in anthropogenic CH_4 sources (Hogan et al., 1991; Shine et al., 1990). Anthropogenic CH_4 is derived from activities which either directly emit CH_4, such as leaks from gas lines and wells, or those that synthesize CH_4 through the anaerobic breakdown of organic matter (Crutzen, 1991). Human activities which produce CH_4 from anaerobic decay include rice paddy cultivation, landfills, and enteric fermentation in domesticated ruminant livestock.

Current atmospheric CH_4 levels are approximately 1.7 $mg{*}kg^{-1}$ by volume (Crutzen, 1991; Watson et al., 1990). Total world natural and anthropogenic CH_4 emissions are estimated to be about 500 Tg per year (Crutzen, 1991). The contribution from anthropogenic sources within the United States is estimated to be 25 - 30 Tg per year (U.S. EPA, 1993a). Globally, terrestrial sources are estimated to contribute a 28 - 37 Tg per year increase in atmospheric CH_4 levels (U.S. EPA, 1993a). Methane produced from enteric fermentation by domesticated livestock is estimated to contribute to 21 percent of total U.S. anthropogenic emissions, with cattle (*Bos* spp.) contributing 95 percent of total livestock emissions (U.S. EPA, 1993a).

Ruminant CH_4 production

Methane is a by-product of the microbial fermentation of carbohydrates contained in the diets of ruminant animals. In the digestion of glucose, carbon dioxide (a) and formate (b) are synthesized and are then converted to CH_4 by the following mechanisms (Fahey and Berger, 1988; Van Soest, 1994):

$$(a)\ CO_2 + 8H \rightarrow CH_4 + 2H_2O$$

$$(b)\ 4HCOOH \rightarrow 3CO_2 + CH_4$$

While CH_4 production is considered to be a sink for dietary energy, it provides a mechanism for the regeneration of NAD^+ (nicotinamide adenine dinucleotide) molecules, and hence results in a greater total yield of a small percent of aerobic respiration ATP (adenosine triphosphate) to the animal (Fahey and Berger, 1988).

Johnson and Johnson (1995) stated that because of the fact that cattle can lose roughly 6 percent of their dietary intake energy as CH_4 there has been substantial research into the estimation of CH_4 production and the reduction of CH_4 emissions. They reviewed the various methods which have been used to estimate the CH_4 emissions of cattle. It is important to consider these methodologies because such studies are used by governmental and global organizations to estimate sources of anthropogenic CH_4 and to plan efforts to reduce greenhouse gasses (Crutzen et al.,1986; U.S. EPA, 1993a; Watson et al., 1990).

Most of the data available on cattle CH_4 production have come from respiration calorimetry enclosure studies, including whole animal chambers, face masks, and hoods (Johnson and Johnson, 1995). Respiration chamber studies involve circulating air within the chamber as the animal eats and respires, with samples of CH_4 being taken at regular intervals (Blaxter and Clapperton, 1965; Johnson and Johnson, 1995). Methane production is calculated by measuring the difference between initial and ending CH_4 levels, taking into account the volume of the animal and characteristics of the chamber, such as temperature, chamber volume, and the volume of gas (Blaxter and Clapperton, 1965).

Johnson et al. (1994) stated that the basis of most ruminant inventories is derived from the study by Crutzen et al. (1986) who in turn based their CH_4 emission estimates on respiration calorimeter chamber studies. In these studies, energy intake from the diets of the animals was partitioned amongst various metabolic pathways, allowing for CH_4 production to be estimated (Johnson et al., 1994). Crutzen et al. (1986) estimated that total annual CH_4 production from cattle on range in the US would be 54 kg per animal.

Statistical models and prediction equations have been used also to estimate CH_4 production (Johnson and Johnson, 1995). These equations allow the characteristics of the feed to be used to calculate CH_4 production, and are derived from CH_4 measurements from calorimetry studies (Johnson and Johnson, 1995). The most commonly used model to predict CH_4 production is that of Blaxter and Clapperton (1965) which is based on data obtained with sheep (*Ovis aries* L.) CH_4 production (Johnson et al., 1994; Johnson and Johnson, 1995). Johnson and Johnson (1995) warned that care should be taken in the implementation of this model because it predicts CH_4 production toward the high end of the range of observed values. The United States Environmental Protection Agency (US EPA) used a model by Baldwin et al. (1987a; 1987b) in its estimation of cattle CH_4 emissions. However, the US EPA (US EPA, 1993a) pointed out that these models are limited because of the small diversity of management practices the models are capable of representing, and that the models are based solely upon calorimetry studies.

The use of statistical models to predict CH_4 production has been criticized, because these models are based on data from respiration chamber studies. Johnson et al. (1994) pointed out that these chamber studies involve pre-determined and pre-set artificial environmental conditions. Animals in respiration chambers are restricted in movement (Johnson and Johnson, 1995). There is some doubt, therefore, as to how well these artificial situations accurately mimic CH_4 production in actual environments, such as in pastures or range, where the movement of animals is not restricted (Johnson et al., 1994; and US EPA, 1993a).

An alternative to respiration 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). The SF_6 tracer method involves placing a permeation tube, with a known permeation rate of SF_6, in the reticulum. Eructated gas samples are then continuously taken through a canister placed on the neck and analyzed for CH_4 and SF_6 concentrations. With a known rate of SF_6 permeation, and known concentrations of CH_4 and SF_6, the CH_4 emission rate for the animal can then be calculated, using the equation:

$$Q_{CH4} = Q_{SF6} \times [CH_4]/[SF_6]$$

where Q_{CH4} = CH_4 emission rate; Q_{SF6} = SF_6 permeation rate; $[CH_4]$ = measured CH_4 concentration; $[SF_6]$ = measured SF_6 concentration (Johnson et al., 1994). Johnson et al. (1994) demonstrated a good correlation between CH_4 emission rate estimates obtained through their SF_6 tracer method and through calorimetry chambers. The implementation of a simple tracer method is believed to allow for more precise estimation of CH_4 emissions from cattle on pastures or open range, and with a variety of forage species.

Tall fescue

Tall fescue (*Festuca arundinacea* Schreb.) is a cool season perennial grass which, since its major spread in the 1940-1950s, has become the predominant forage in the transition zone of the eastern U.S. (Stuedemann and Hoveland, 1988). Tall fescue quickly gained popularity among farmers, due to its ease of establishment, range of adaptation, length of growing season, good seed production, and tolerance of abuse, pests and drought (Stuedemann and Hoveland, 1988; Fribourg et al., 1991; Arachevaleta et al., 1988). About 14 million ha are currently grown in the U.S. (Buckner et al., 1979), with 1.5 million ha grazed by cattle in the state of Tennessee (Fribourg et al., 1991).

Tall fescue toxicosis

Problems with poor performance of animals grazing tall fescue have been observed since at least the 1950s (Pratt and Haynes, 1950; Pratt and Davis, 1954). The decreased animal performance is characterized by diminished weight gains, heat intolerance, slightly elevated body temperatures, rough haircoat, reduced consumption, and decreased calving rate, and is known as tall fescue toxicosis (Fribourg et al., 1991; Stuedemann and Hoveland, 1988). In 1973, J.D. Robbins, C.W. Bacon, and J.K. Porter deduced that the presence of a fungal endophyte, found earlier in New Zealand, might be responsible for tall fescue toxicosis (Fribourg et al., 1991; Stuedemann and Hoveland, 1988). A tall fescue seed diet in comparison to the orchardgrass diet. Furthermore, they reported that while steers on the orchardgrass diet gained 6.2 kg during the 3-week trial, the steers consuming the tall fescue seed lost an average of 14 kg during the 3-week trial.

Tall fescue management strategies

The reported effects of fungal endophyte on steer ADG have led to research involving the management of tall fescue pastures to eliminate or reduce the effects of tall fescue toxicosis on grazing animals (Fribourg et al., 1988). While it is possible to change completely E+ tall fescue pastures into E- pastures with intensive and costly procedures, researchers warn that the presence of a fungal endophyte is related to an increase in host plant stress tolerance and longevity (Fribourg et al., 1988). The relationship between the endophyte and tall fescue is symbiotic in nature, since the endophyte has access to plant nutrients, and the tall fescue plant has an enhanced ability to tolerate environmental stresses and herbivory from presence of the endopyte. Studies have found that endophyte presence is linked to tall fescue tolerance to insects (Johnson et al., 1985; Clay et al., 1985) and soil nematodes (Pedersen et al., 1988), and accompanies decreases in small mammal population densities (Coley et al., 1995).

Arachevaleta et al. (1988) studied the effects of endophyte presence on tall fescue drought tolerance. They found that E+ tall fescue had improved drought resistance, and concluded that "endophyte presence is ... an advantage for survival (Arachevaleta et al., 1988)." West et al. (1993) observed enhanced tiller density and survival in endophyte infected tall fescue plants under severe water deficit conditions. Elbersen et al. (1994) studied the effects of endophyte presence in tall fescue during periods of drought stress. They found that endophyte presence reduced water loss from the plant during periods of drought stress, and concluded that endophyte presence may predispose the plant to close its stomates earlier than non-infected plants (Elbersen et al., 1994).

Studies of tall fescue management practices which preserve the stress tolerances imparted by endophyte presence have been conducted. Collins and Balasko (1981) studied the effects of nitrogen (N) fertilization on the quality of stockpiled tall fescue. They observed that N fertilization would generally increase the forage quality of tall fescue.

Many studies have also been conducted on the effects of the inclusion of legumes in E+ tall fescue pastures. Mitchell et al. (1986) found that overseeding of tall fescue pastures with ladino clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), and Kobe lespedeza (*Kummerowia striata* [Thunb.] Schindler) resulted in a 27 percent higher ADG of steers than those steers grazing tall fescue fertilized with N. Chestnut et al. (1991) studied the effects on steer performance of inclusion of bermudagrass (*Cynodon dactylon* L.) and clover in E+ tall fescue pastures. They observed some alleviation of the decreased ADG, decreased beef production, and rough haircoats associated with tall fescue toxicosis in E+ pastures containing bermudagrass. They observed also an increase in beef production on E+ tall fescue pastures with ladino clover, relative to E+ tall fescue pastures fertilized with N; however, they did not report any benefit to including clover in E+ tall fescue pastures relative to E- tall fescue pastures.

McMurphy et al. (1990) also studied the effects on beef production of clover inclusion in E+ tall fescue pastures in comparison to E- and E+ pastures without clover. They found that inclusion of clover in E+ tall fescue pastures could reduce the effects of tall fescue toxicosis on steers. This was evident in similarity between steer ADG on the E- tall fescue and E+ tall fescue with clover pastures.

Summary and statement of objectives

Methane produced by enteric fermentation in domesticated livestock is of interest because it represents an energetic inefficiency of microbial fermentation and because of the role CH_4 is suspected of playing in global warming scenarios. Estimation of the intensity of various sources of CH_4 is important in the implementation of mitigation scenarios. The SF_6 tracer method of Johnson et al. (1994) has merit because it allows for the estimation of CH_4 production under normal foraging situations, rather than within the confines of the artificial environments of respiration calorimeter chambers. Cattle represent an overwhelming majority of the source of CH_4 emissions by domesticated livestock in the US. Tall fescue is an ideal forage for studying CH_4 production because it is an important forage in the eastern United States, and the toxic syndrome associated with cattle grazing E+ tall fescue can be mitigated with management strategies which improve the performance of cattle grazing E+ tall fescue pastures.

The objectives of this study were: (1) to use CH_4 production as an indicator of beef cattle productivity on tall fescue pastures, (2) to determine the effects of tall fescue management systems on beef productivity, and (3) to contribute to a national CH_4 production database for beef cattle.

II. MATERIALS AND METHODS

This study was designed to measure the CH_4 emissions from beef cattle grazing pastures without restraints on movement and activity. Data were collected during the spring and summer of the 1997 grazing year, and during the winter and spring of the 1998 grazing year.

Pastures

Pastures which were already part of a grazing study at the Blount Unit (35°49′N, 83°13′W) of the Knoxville Experiment Station were used. Eight of the twenty-four 1.2 ha pastures at the Blount Unit were used to measure CH_4 from cattle grazing tall fescue pastures. The pasture systems used to measure CH_4 emissions from the experimental animals were: (1) E+ tall fescue, (2) E- tall fescue, (3) E+ tall fescue/clover, and (4) alternating groups of four 20-cm drill rows of E+ and E- tall fescues.

Two pastures of about 4 ha each at the Holston Unit (35°57′N, 83°51′W) of the Knoxville Experiment Station were also used to measure CH_4 emissions from grazing cattle. The pasture systems used at the Holston Unit were: (1) an unimproved pasture (UP) typical of the region (tall fescue, bermudagrass, Kentucky bluegrass (*Poa pratensis*), other grasses and weeds), and (2) a well managed E+ tall fescue/clover pasture (Best Management Practices = BMP) typical of the region.

Phosphorous (P) and potassium (K) fertilizers were applied to all the pastures (except for the unimproved pasture at the Holston Unit) in winter or early spring of each year to maintain a medium soil test level of fertility. In early spring and early September of each year, all pastures except the pastures containing clover and the unimproved pasture at the Holston Unit received 56 kg N per ha applied as ammonium nitrate (NH_4NO_3).

The unimproved pasture at the Holston Unit has received no inputs in pasture management, such as fertilization, seeding of improved species, and mowing, in the recent past. All other Holston and Blount pastures were managed so that there were between 900 and 1500 kg_*ha^{-1} of available dry matter forage at all times, as estimated every 21 days with 53.3 x 304 cm clipped forage strips. This provided enough forage to allow adequate voluntary intake by the cattle. Available forage, forage quality and dry matter intake were measured as part of the larger study, but are not included here. Within each pasture, artificial shade, fresh water, and mineralized salt were provided to the experimental animals.

Experimental animals

Two steers (Angus or Angus x Hereford, *Bos taurus* L.) were placed on each pasture of the four treatments at the Blount Unit, and two pastures (replications) of each of these systems were used. Four steers and four cow/calf pairs were placed on each unreplicated pasture at the Holston Unit.

The steers used in the first year of this study were weaned stockers selected from the Knoxville and the Plateau Experiment Stations from the spring 1996 calf crop, and the steers used in the second year of the study were weaned stockers selected from the spring 1997 calf crop. The mature (> 3-year old) cows from the Knoxville Experiment Station spring calving herd were pregnancy checked in fall 1996 and again in fall 1997. Two of the eight cows used in 1997 were not pregnant before the start of the 1998 grazing year, and were replaced with two pregnant cows. All animals used were selected on the basis of age, weight, and body condition.

Experimental animals were fitted with practice halters and collection canisters to accustom them to the sampling devices for one week prior to first use. The experimental animals were weighed every 21 days while on pasture. Body condition scores on a 9-point scale were recorded for cows at the beginning of the spring 1997 and at the end of the summer 1997 grazing season (Herd and Sprott, 1986).

The sulfur hexafluoride tracer method

The SF_6 tracer gas method developed at Washington State University (Johnson et al., 1994) was used to measure the CH_4 emissions from the steers and cows on the experimental pastures. The SF_6 tracer method involves placing a permeation tube (Figure 1), with a known SF_6 permeation rate, in the reticulum. Eructated gas is then constantly sampled through a collection device (Figure 2) placed on the neck of the animal. Knowing the rate of SF_6 permeation from the tube, and measuring concentrations of CH_4 and SF_6 in the collection canister, the CH_4 emission rates from each animal then can be calculated.

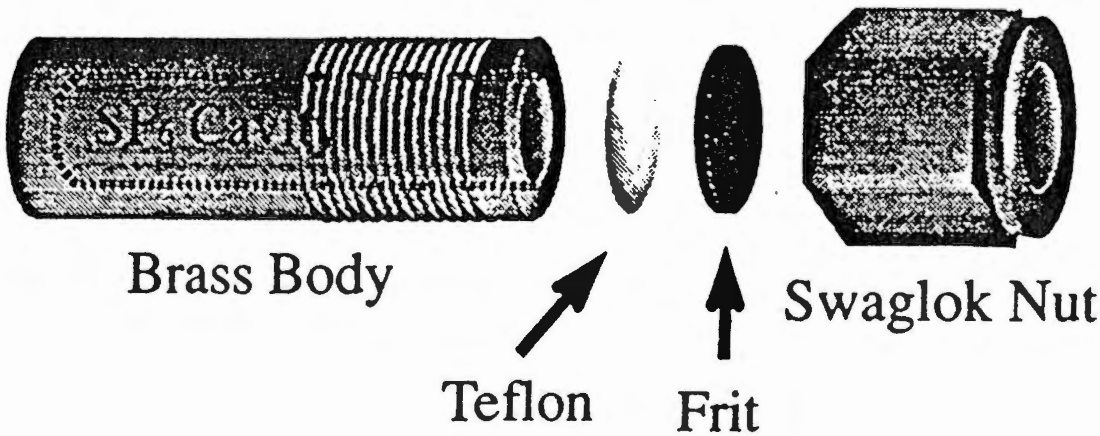

Figure 1. Permeation tube (tube length 3.175 cm) (from Westberg et al., 1996).

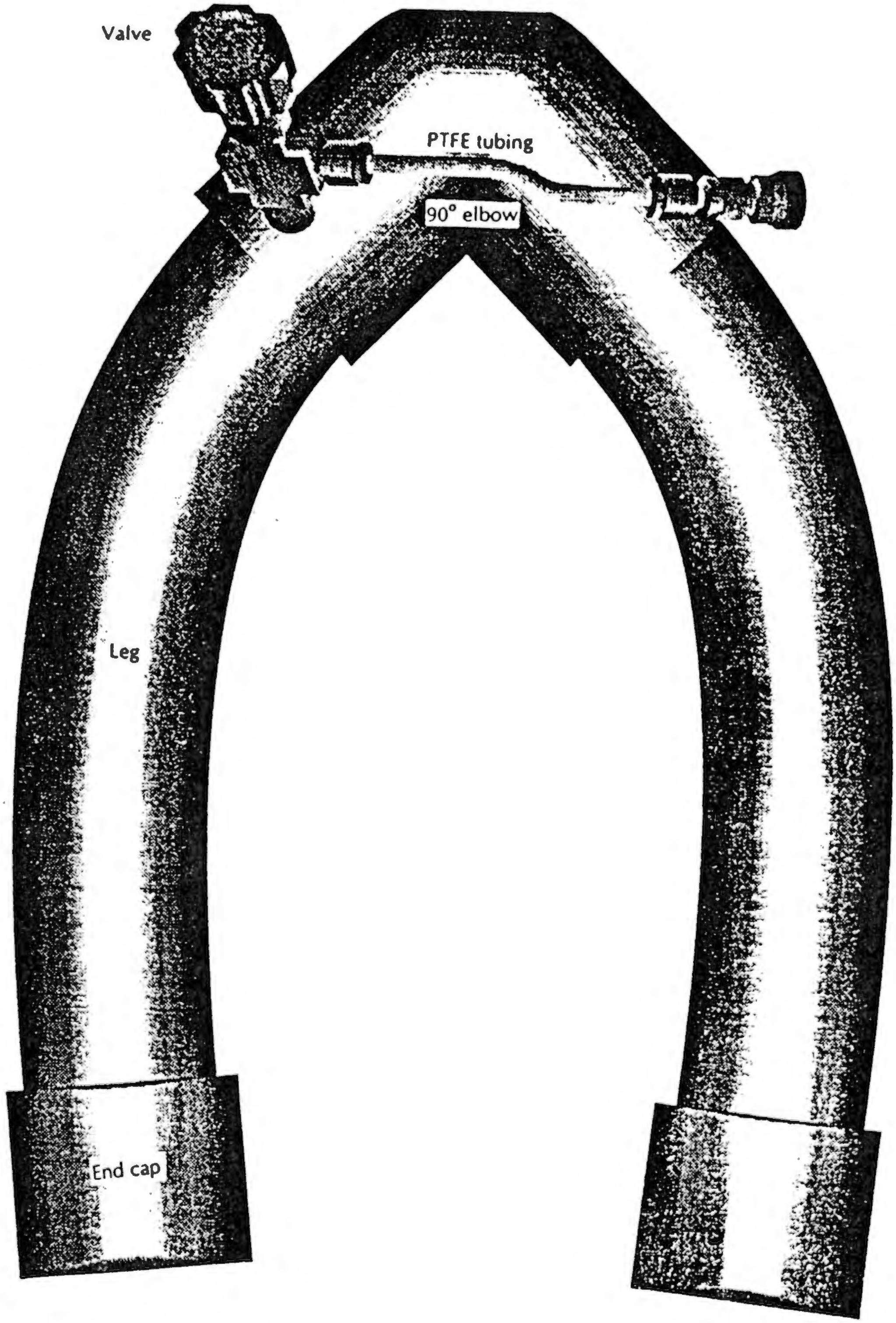

Figure 2. Collection canister (leg 50.8 cm long) (from Westberg et al., 1996).

Laboratory spaces

Sulfur hexafluoride molecules tend to reside in plastics and other materials to which they are exposed. In order to prevent contamination with SF_6, and to provide better laboratory space for the gas chromatograph (GC), three separate laboratories were established at the University of Tennessee.

Two laboratories were utilized in the Animal Sciences building. The first one housed only the GC and supporting equipment, and was kept free of contaminants which would interfere with GC analysis. The second Animal Sciences laboratory was used as a work space. In this location, collection halters and canisters were constructed and repaired, tools and replacement equipment were stored, and collection canisters were prepared for both collection and GC analysis.

A separate laboratory was established in the Plant and Soil Sciences building. In this laboratory, the permeation tubes were filled with SF_6, and the balance and water bath used in calibrating the tubes were housed.

Permeation tubes

Each permeation tube was a 3.175-cm long brass capsule, fitted with a swagged nut, stainless steel frit, and a thin piece of Teflon, through which SF_6 was emitted (Figure 1). The tubes were obtained, filled, and calibrated in the fall of 1996 and spring of 1997. The tubes were immersed in liquid N, and then filled with SF_6 by syringe so that approximately 0.6 g of SF_6 was in each individual tube. Tubes were then placed in a flask fitted with a rubber stopper which dependent upon the temperature of the gas. The air exiting the flasks was vented out of the laboratory with a fume hood to prevent the accumulation of SF_6 in the laboratory.

After using the 3.175-cm long tubes in 1997, it was decided that the length of the permeation tubes should be increased for the animals that would be grazing pastures beginning the winter 1998 grazing season. The tube length was increased to allow more SF_6 to be injected into the tubes in order to: (1) increase the length of time that a tube would give off SF_6 in the experimental animal, and (2) increase the concentration of SF_6 in the collected samples, so as to allow easier detection with the GC. The length of the brass capsule was increased to 5.08 cm, and each tube was filled with approximately 1.0 g of sulfur hexafluoride.

The emission rates for all the permeation tubes were calibrated by weighing the tubes weekly for two months in the laboratory. A weight decay emission rate was then calculated for each tube. Permeation tubes with an emission rate of greater than 800 $ng{*}min^{-1}$ were selected for administration to the experimental animals.

Collection devices

Collection canisters were constructed from 50.8-cm lengths of 5.08-cm diameter 1.104×10^6 Pa white PVC tubing (Figure 2). The canisters were heated until pliable in an oven, and then were bent into an ox-bow shape. A valve connected by Teflon (polytetrafluoroethylene [PTFE]) tubing to a quick-connect was attached to the top of the canisters. The quick connect could be attached to

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The collection halters were large, adjustable horse halters, fitted with a leather patch sewn on top of the muzzle to secure the filter end of the tubing system to the halter (Figure 3). The tubing system used on the halters consisted of a 35.56-cm length of 0.127-mm inside diameter stainless steel capillary tubing. The length and diameter of the capillary tubing determined the flow rate of air through the tubing, and was selected to allow about a 27-hour sample to fill each collection canister. The capillary tubing was attached to a 45.72-cm length of flexible Teflon tubing. A quick-connect attached to the other end of the Teflon tubing allowed the system to be connected to the collection canisters. The tubing system was checked for leaks with a mixture of alcohol and water, and then attached to the halter with black electrical tape. The tape was applied loosely, so that there was some room for the tubing system to move laterally,

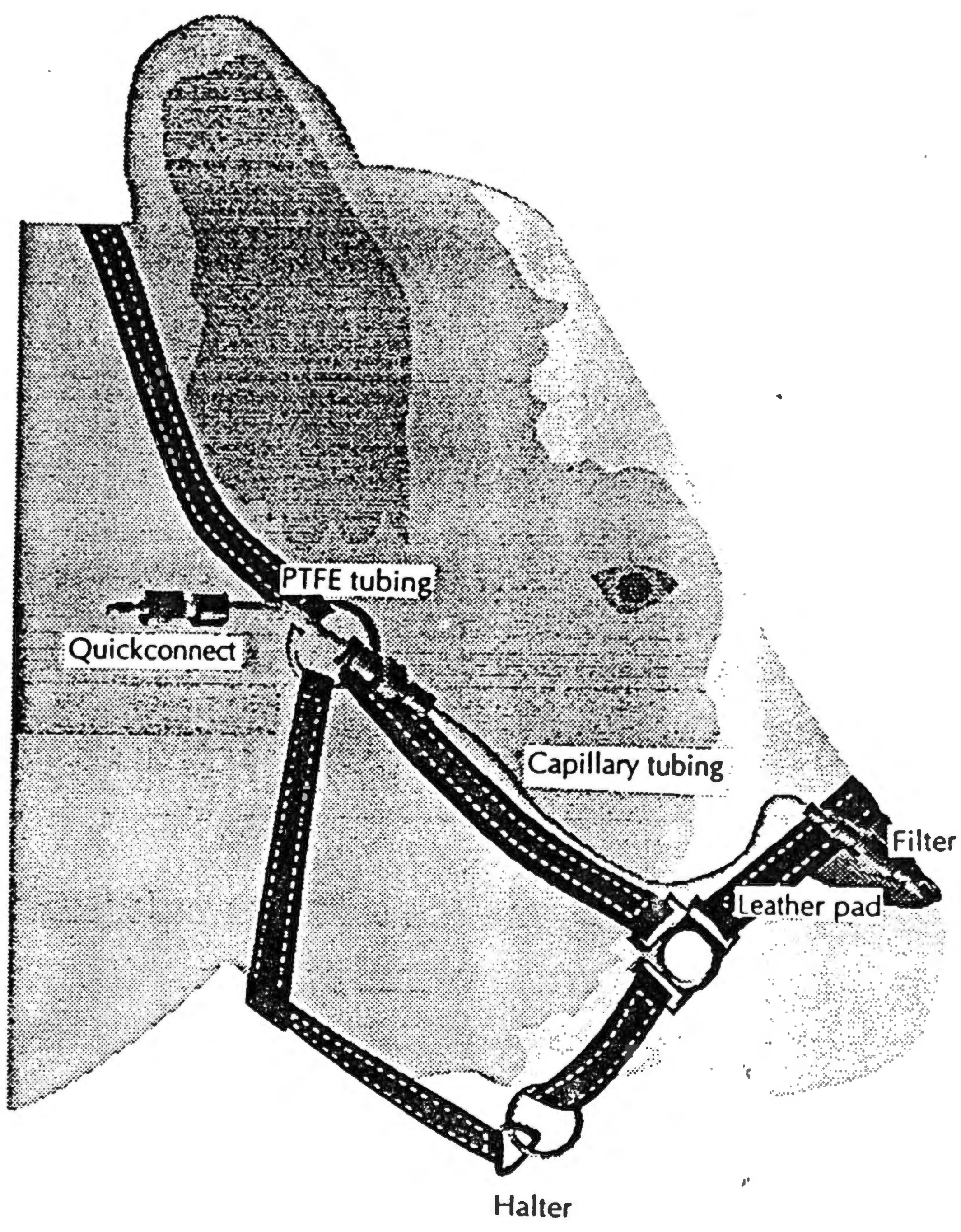

Figure 3. Collection halter (from Westberg et al., 1996).

should the animal catch it on obstructions in the field. An in-line 15-µm Nupro filter was attached to the end of the stainless steel tubing. The system was checked for leaks again, and was also checked to determine whether sufficient airflow passed through the filter and capillary system by running compressed N gas through the tubing. The filter was then placed in an appropriate length of 2.54-cm diameter PVC tubing for protection and was attached to the leather patch with three cable ties. The leather patch and therefore the filter inlet could then be placed on top of the muzzle, between the nostrils of the animals. The collection canister and collection halter together weighed about 240 g.

Methane sampling

Methane sampling periods of 1 week were conducted on the eight pastures at the Blount Unit in late April/early May, June, July, and August 1997, and in January, April, May, and June 1998. One-week sampling periods were conducted on the two pastures at the Holston Unit in May, June, July, and August 1997, and in February, May, and June 1998. Steers only were on experimental pastures at the Holston Unit at the time of the February 1998 sampling period because the cows were giving birth to their calves. Sampling periods began on Monday in the early morning, and ended the following Saturday morning. Five 24-hr CH_4 samples per animal were taken each week.

About one week prior to the first sampling period at each unit each year, a permeation tube was administered with a balling gun to each experimental animal. At the end of the summer grazing season the tubes were removed surgically by rumenotomy from the steers. All animals that had permeation tubes removed were held by the Knoxville Experiment Station for a minimum of 120 days prior to dispersal or sale in accordance to the Department of Health and Human Services Investigational New Animal Drug (INAD) file number 9542.

On the first day of a sampling period, in the early morning, collection canisters were attached to a vacuum pump in the laboratory, and were drawn to a vacuum of less than 6.9×10^3 Pa. This made for a constant pull of expelled air samples through the halter tubing system into the canisters.

At each field experimental facility, the animals were brought to a corral chute in the early morning. There, they were driven into the head gate, where the sampling equipment was placed on each animal. At first, a halter was placed on the animal so that the filter would be located between the nostrils, but high enough on the muzzle to minimize interference with drinking and grazing. A collection canister was then placed on the neck of the animal, with the valve facing forward. The canister was secured to the halter with a velcro strip, and swivel hooks attached to the canister with cable ties were locked onto the sides of the halter. Once the canister was secure, the quick-connects on the canister and halter were linked securely. The quick-connect linkage was protected by surrounding it with a short length of 5.08-cm diameter PVC tubing. The PVC, and hence the quick-connects, were attached to the halters with a velcro strip to prevent the animals from snagging the lines and separating the quick-connects in the field. The valve on the canister was opened, and the starting time of the sampling was noted. The animals were then returned to the appropriate pastures.

Canisters were also placed near the experimental pastures to monitor background levels of CH_4 and SF_6 daily during each sampling period. Care was taken to avoid driving or parking vehicles close to these “background canisters,” as components of motorized vehicle exhaust would interfere with the GC analysis of SF_6 in the canister. Background levels of CH_4 and SF_6 were not considered large enough to warrant inclusion in the calculation of daily cattle CH_4 emissions.

On the morning following the placement of canisters on each animal, vacuums were created in fresh canisters. The animals were again brought to the handling facilities and, while there, the canister from the previous day was removed. The pressure in each canister was checked on site because canister pressure was used an indicator of sample flow through the collection system. A pressure reading between 5.52×10^4 Pa (8 PSI) and 7.59×10^4 Pa (11 PSI) indicated that the tubing system was functioning properly. A reading similar to atmospheric pressure indicated a leak in the collection system. A pressure reading that was lower than 5.52×10^4 Pa (8 PSI) indicated blockage of sample flow through the collection system. The halters on each animal were also visually inspected for clogs and rips in the collection system. Faulty halters were replaced, and the previously described method was repeated to place new canisters on the animals.

The used canisters were taken back from the farm to the Animal Sciences laboratory for analysis. Each canister was pressurized with N gas to about

1.242×10^5 Pa, allowing for auto-pressure injection into the GC. A GC fitted with an electron capture detector (ECD) and flame ionization detector (FID) was used to determine the concentrations of SF_6 and CH_4, respectively, in the canister gas samples. Two sub-samples of each canister were run through the GC for analysis. The SF_6 and CH_4 concentrations were used along with the known permeation rate for the permeation tubes in each animal to calculate a daily CH_4 emission rate for each experimental animal.

Methane calculation

In this section, the method of calculation of a daily CH_4 emission from an animal is presented to illustrated the calculation conducted on each sample taken during the collection period. The following equation was used to estimate the emission from each animal in this study:

$$Q_{CH4} = Q_{SF6} \times [CH_4]/[SF_6],$$

where Q_{CH4} = CH_4 emission rate ($g{*}min^{-1}$); Q_{SF6} = SF_6 permeation rate ($g{*}min^{-1}$); $[CH_4]$ = measured CH_4 concentration ($\mu g{*}m^{-3}$); $[SF_6]$ = measured SF_6 concentration ($\mu g{*}m^{-3}$). The SF_6 emission rate was determined from the decay rate derived from laboratory calibration of the permeation tube in the animal. The sample CH_4 and SF_6 concentrations were obtained through analysis of the daily sample with the GC. Although the concentrations were expressed as $\mu g{*}m^{-3}$ in the equation, the readings from the GC were expressed in parts per million (PPM) for the CH_4 and parts per trillion (PPT) for the SF_6. To convert the GC readings, the sample concentrations were multiplied by the molecular weights of CH_4 and SF_6, 16 atomic mass unit (amu) and 146 amu, respectively, before being entered into the equation.

As an example, if a sample canister was obtained from an animal with a permeation tube having a SF_6 permeation rate of 9.57×10^{-7} g*min^{-1}, and the GC analysis of the sample provided the following concentrations: CH_4 = 29.55 PPM; SF_6 = 24.08 PPT, the following calculation would be made. Adjusted for molecular weight, these concentrations are entered into the equation as 19336 µg*m^{-3} and 0.144 µg*m^{-3}, to give:

$$Q_{CH4} = 9.57 \times 10^{-7} \text{ g*min}^{-1} \times [19336 \text{ µg*m}^{-3}] / [0.144 \text{ µg*m}^{-3}].$$

The CH_4 emission rate for this animal then would be calculated to be 0.13 g*min^{-1} or, when expressed on a daily basis, 187 g CH_4*d^{-1}.

Statistical analysis and data considerations

The data were analyzed by analysis of variance (ANOVA) using the MIXED procedure of SAS (1985).

Steer starting weights and ADG for 1997 and 1998 at the Blount Unit were analyzed using the model:

$$y_{ijkl} = treat_i + past(treat)_{ij} + anim*past(treat)_{ijk} + seas_l + treat*seas_{il},$$

where y=starting weight or ADG, treat=pasture system, past=pasture number, anim=animal number, and seas=grazing season.

Methane emissions for 1997 and 1998 at the Blount Unit were analyzed using the model:

$$y_{ijklm} = treat_i + past(treat)_{ij} + anim*past(treat)_{ijk} + seas_l + per(seas)_{lm} + treat*seas_{il} + treat*per(seas)_{ilm},$$

where $y=CH_4$ emission, treat=pasture system, past=pasture number, anim=animal number, seas=grazing season, and per=sampling period.

When data were combined from 1997 and 1998 for steers at the Blount Unit, the following model was used:

$$y_{ijklmn} = treat_i + past(treat)_{ij} + anim*past(treat)_{ijk} + year_l + seas_m + per(seas)_{mn} + treat*year_{il} + treat*seas_{im} + treat*per(seas)_{imn},$$

where $y=CH_4$ emission, treat=pasture system, past=pasture number, anim=animal number, year=year, seas=grazing season, and per=sampling period.

Cattle starting weights and ADG at the Holston Unit were analzed using the model:

$$y_{ijkl} = treat_i + class(treat)_{ij} + anim*class(treat)_{ijk} + seas_m + seas*class(treat)_{ijm},$$

where y=starting weight or ADG, treat=pasture system, class=animal class, anim=animal number, and seas=season.

Methane emissions from 1997 and 1998 for cattle at the Holston Unit were analyzed using the model:

$$y_{ijklm} = treat_i + class(treat)_{ij} + anim*class(treat)_{ijk} + seas_l + per(seas)_{lm} + seas*class(treat)_{ijl} + class*per(treat*seas)_{ijlm},$$

where y=CH_4 emission, treat=pasture system, class=animal class, anim=animal number, seas=grazing season, and per=sampling period.

The models generated least squares means which were analyzed using the *pdiff* option of the MIXED procedure. The *pdiff* option separated least square means using least significant difference. A probability value of α = 0.05 was used for rejecting the null hypothesis in all statistical tests.

The CH_4 emissions were analyzed as grams of daily CH_4 emissions per animal. Methane emissions were also analyzed in function of both ADG and metabolic weight. Each CH_4 emission recorded for each animal was divided by either the corresponding ADG (in kg) for the appropriate time period or by 100 kg of metabolic weight (body weight in KG to the 3/4 power) for each animal (NRC, 1996).

III. RESULTS AND DISCUSSION

General considerations

Methane emissions for cattle grazing pastures at the Blount Unit during the 1997 spring and summer and the 1998 spring grazing seasons were analyzed for each year and also combined into one data set. All other data were analyzed separately by year due to either small numbers of observations or because of only one sampling period in the winter 1998 grazing season.

Methane emissions are reported as daily emissions per animal, daily emissions as a function of ADG per animal, and daily emissions as a function of 100 kg of metabolic weight per animal. Reporting CH_4 emissions as a function of ADG provides a measure of efficiency, as it considers the CH_4 emission per unit of animal performance. Expressing CH_4 emissions as a function of metabolic weight factors the size of an animal into the emission rate, as body mass has been shown to be related to energy expenditure (Ferrell, 1988; Burrin et al. 1990).

Sampling considerations

A total of 1200 CH_4 samples were possible during the 15 collection periods. It should be recognized that the collection of the samples required much time, many resources, and considerable skilled and unskilled labor.

Construction of the collection canisters and halters required three skilled and at least two unskilled laborers. Two skilled and two to four unskilled laborers were required for the physical collection of the samples (including placing the collection devices on the animals, recording data, and working cattle). One skilled laborer was needed to analyze the samples with the GC, while two skilled laborers were needed to calibrate and fine-tune the GC. One skilled and two to four unskilled laborers were needed to repair defective collection canisters and halters.

Filling the permeation tubes (100 tubes in 1997 and 70 tubes in 1998) and calibrating the emission rates of the permeation tubes took about 36 hours. Construction of each collection canister took about 40 minutes. Each day of collection had 16 sample canisters and 2 to 4 background canisters. The collection canisters were reusable, but one hundred collection canisters were constructed to provide sufficient canisters for one sampling period, totaling about 66.5 hours. Construction of the tubing system, calibrating the sampling rate, and installing the tubing system on the halter took about 45 minutes per halter. Fifty halters were constructed, totaling 37.5 hours.

Working cattle, recovering canisters containing samples, replacing collection canisters and halters, and recording data took about three hours per day during the sampling periods. Pressurizing the collection canisters with N gas and creating vacuums in fresh canisters took about an hour per day during the sampling periods. Analyzing the samples with the GC took between four and seven hours per day. Repairing breaks and leaks in the tubing system, replacing missing elements on the collection halters, and repairing leaks in the canisters took between two and five hours per day during the sampling periods.

Factoring in the time for construction of the sampling devices, physical collection of the samples, preparation of the collection canisters, analysis of the samples, and repairs of the collection devices, between 45 to 65 minutes of labor were spent for each of the 1200 total CH_4 samples. Between 75 and 85 percent of the total possible collected samples during each sampling period were actually collected and usable. Sample losses were due primarily to clogging of the halter system with water. The sampling technology had been previously used in the Western U.S. under drier conditions that those existing in Tennessee. Other causes of sample losses included accidental disconnections between the canister and the halter systems by the animals, broken canisters, and breaks in the halter system. The halter system breaks occurred primarily at the union of the capillary tubing and the in-line filter. This was because of the design of the waterers in the pastures, which allowed the animal to snag the filter inside the waterer while drinking, and to break the connection to the capillary tubing when finished drinking. The halter systems were broken in a similar fashion if the animal snagged the filter on some other obstruction in the pasture. Breaks in the flexible Tygon tubing of the halter system occurred from the tubing being caught by the animal on an obstruction in the pasture.

Cattle at the Blount Unit

Performance data

Steers on the four pasture systems did not differ in mean starting weight for the spring 1997, winter 1998, and spring 1998 grazing seasons (Table A-1).

Steers grazing the E- tall fescue and E+ tall fescue/clover pastures had higher mean starting weights in the summer 1997 season than steers grazing the E+ tall fescue and E+/E- tall fescue pastures because of numeric differences in steer ADG during of the preceding spring (Table A-1).

Among pasture systems, ADG did not differ for the spring 1997 season (Figure 4; Table A-1). Average daily gain for the summer 1997 season was lower for steers grazing the E+, E-, and E+/E- tall fescue pastures than for the steers grazing the E+ tall fescue/clover pastures (Figure 4; Table A-1). The presence of clover in an E+ tall fescue pasture resulted in a 50 percent increase in ADG. Chestnut et al. (1991) attributed increased steer ADG in tall fescue pastures which contained clover to the consumption of better quality forage.

Average daily gain for steers grazing all four pasture systems increased during the spring 1998 season when compared with the winter 1998 season (Table A-1). During the winter 1998 season, steers grazing the E+ tall fescue pastures had lower ADG than the other pasture systems (Table A-1). In the spring 1998 season, steers grazing the E- tall fescue and the E+ tall fescue/clover pastures had higher ADG than steers grazing E+ tall fescue and E+/E- tall fescue pastures (Table A-1).

While the relationship between ADG for steers grazing the E+ tall fescue and E+ tall fescue/clover pastures in the summer 1997 season and the spring 1998 season was similar to that reported elsewhere, the actual ADG for these pastures and seasons were higher than those reported by other workers.

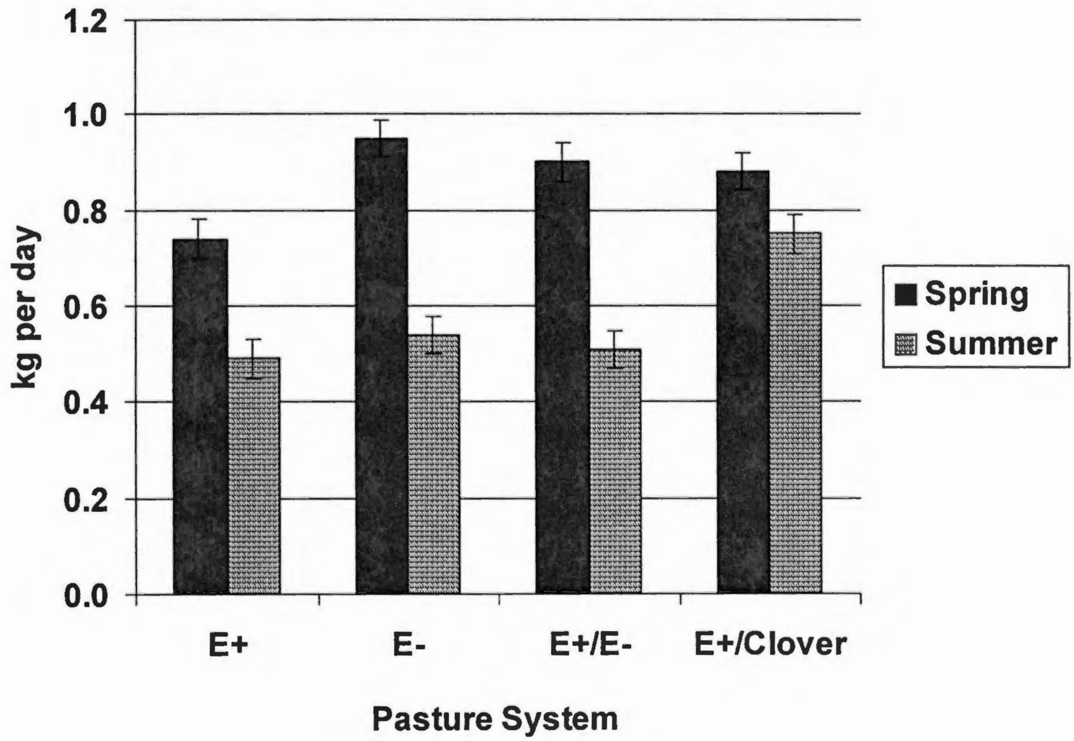

Figure 4. Seasonal ADG for steers grazing tall fescue pastures at the Blount Unit in 1997.

Thompson et al. (1993) reported mean summer ADG of 0.37 $kg_{*}d^{-1}$ and 0.51 $kg_{*}d^{-1}$ for steers grazing E+ tall fescue and E+ tall fescue/clover pastures, respectively. The ADG reported by Thompson et al. (1993) were derived from a pooling of data sets from several years of studies at several locations, providing the authors with data from a broad range of climatic conditions. The difference between the ADG reported here and those by Thompson et al. (1993) could be due in part to the higher than normal precipitation in the Knoxville area during spring and early summer 1997, and spring 1998 grazing seasons (Figure B-1).

Methane emissions

When the spring and summer 1997 and spring 1998 emissions were analyzed together, mean daily CH_4 emissions for steers grazing E+, E-, and E+/E- tall fescue pastures were greater in the spring than in the summer (Figure 5). Mean daily CH_4 emissions for steers grazing E+ tall fescue/clover pastures were higher in summer than in spring (Figure 5). There were no differences among mean daily emissions for the four pasture systems in the spring; however, in the summer, cattle grazing the E+ tall fescue/clover pastures emitted more CH_4 per day than cattle grazing the E+ and E+/E- tall fescue pastures (Figure 5). Mean CH_4 emissions as a function of metabolic weight among the pasture systems followed a relationship similar to those for the mean daily emissions (Figure 6). However, the trend for the seasons was reversed, as the mean emissions as a function of metabolic weight in the spring were higher than those in the summer (Figure 6). This is due to the fact that the cattle were heavier in summer than in the preceding spring season (Table A-1).

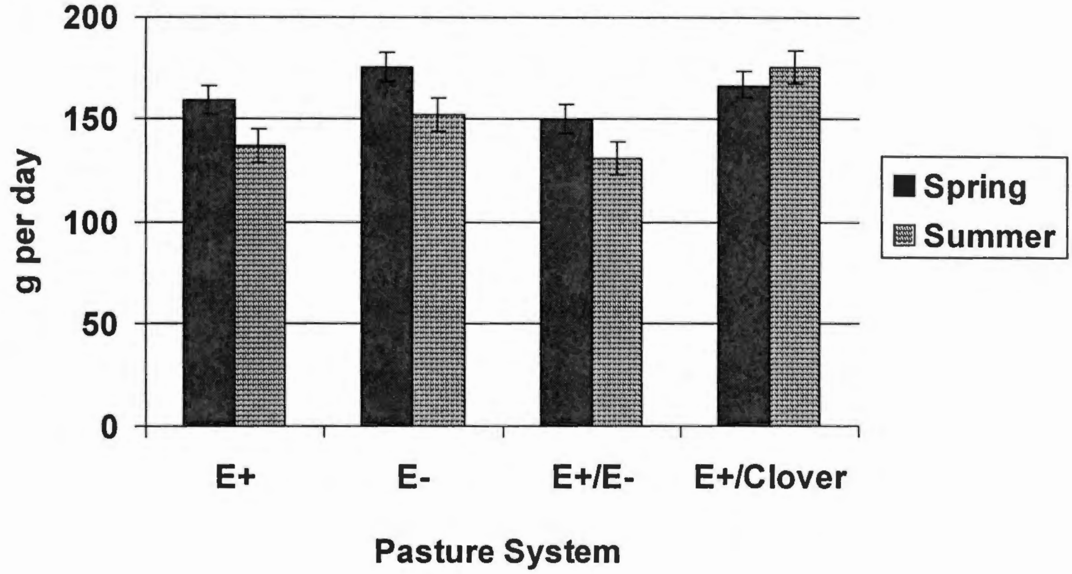

Figure 5. Least squares mean seasonal CH_4 emissions for steers grazing tall fescue pastures at the Blount Unit in 1997 and 1998.

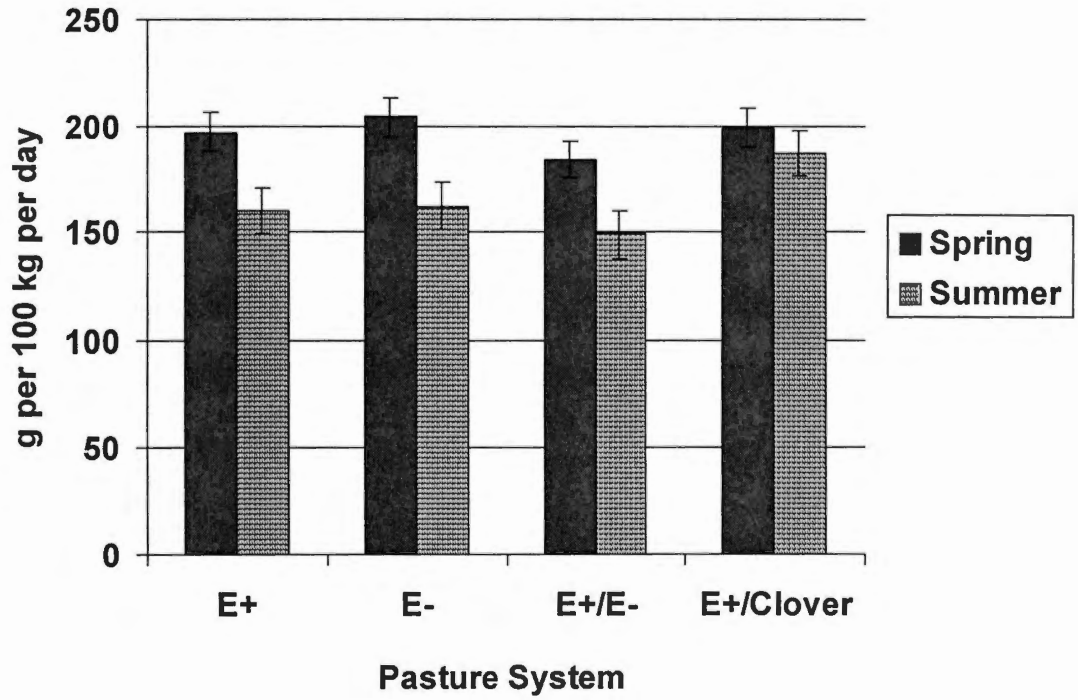

Figure 6. Least squares mean seasonal CH_4 emissions expressed as a function of metabolic weight for steers grazing tall fescue pastures at the Blount Unit in 1997 and 1998.

The mean CH_4 emissions as a function of ADG were generally greater in spring than in summer (Figure 7). In spring, steers grazing the E+ tall fescue pastures emitted a numerically greater amount of CH_4 per kg of gain than steers grazing the other three pastures (Figure 7). In summer, steers grazing the E+ tall fescue/clover pastures emitted 18 to 20 percent less CH_4 per kg gain than cattle grazing the other three pasture systems (Figure 7).

When the 1997 steer CH_4 emission data were analyzed alone, the mean daily emissions for steers grazing E- tall fescue and E+ tall fescue/clover pastures were higher than those for steers grazing E+ tall fescue and E+/E- tall fescue pasture (Table C-1). A similar trend was found during the summer 1998 season and, with the exception of the steers on the E+ tall fescue/clover pasture, summer mean daily emissions were lower than those in spring (Table C-1). These relationships were also observed between the mean CH_4 emissions in terms of metabolic weight for steers grazing the four pasture systems, except that those for the steers on the E+ tall fescue/clover pasture were higher than those for the other three pasture systems in summer 1997 (Table C-1).

Mean CH_4 emissions as a function of ADG did not differ among the pasture systems during spring 1997 season (Table C-1). The mean CH_4 emissions as a function of ADG for the steers grazing E- tall fescue were higher than the means for steers grazing the other three pasture systems during summer 1997 (Table C-1). The mean CH_4 emissions as a function of ADG were numerically lower for the steers grazing the E+ tall fescue/clover pastures than for the steers grazing the E+ tall fescue pastures during summer 1997.

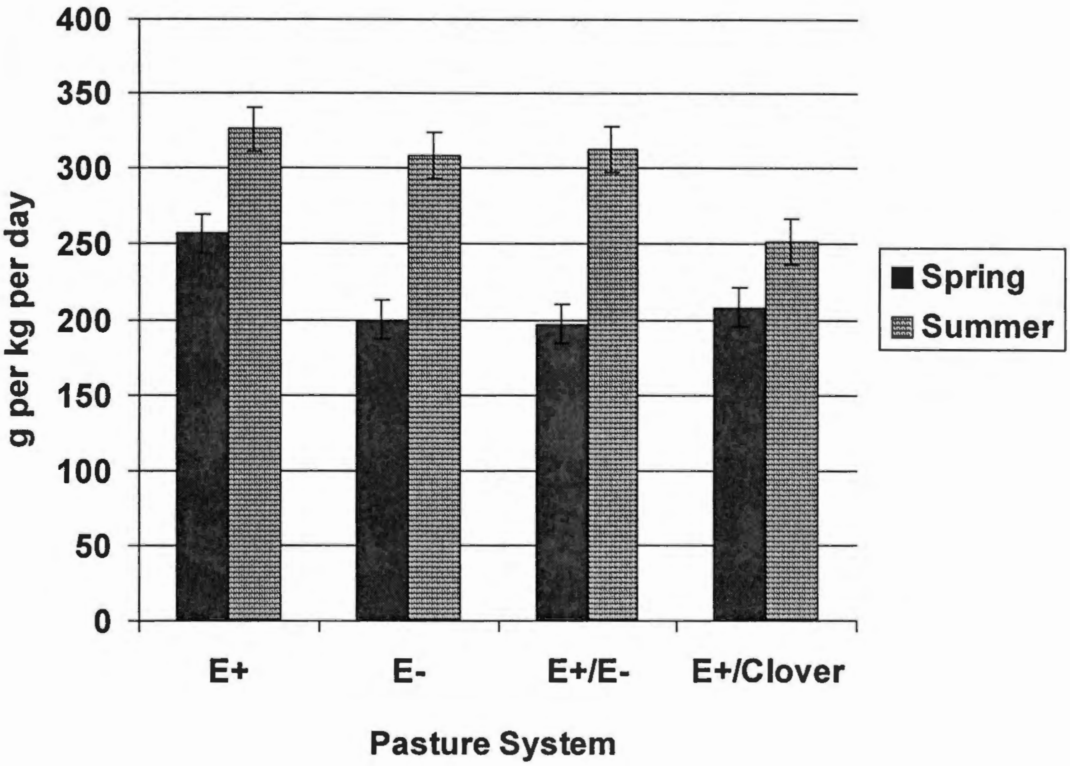

Figure 7. Least squares mean seasonal CH_4 emissions expressed as a function of ADG for steers grazing tall fescue pastures at the Blount Unit in 1997 and 1998.

There were no differences among the mean daily CH_4 emissions between the pasture systems within both winter and spring 1998 grazing seasons (Table C-1). Daily steer CH_4 emissions were higher for all pasture systems during spring 1998 than during winter 1998 (Table C-1). Except for steers grazing the E+ tall fescue pastures, the mean steer CH_4 emissions as a function of metabolic weight did not differ between the winter and spring grazing seasons (Table C-1).

Mean CH_4 emissions as a function of ADG were lower for all pasture systems except the E+ tall fescue during the spring 1998 season than during the winter 1998 season (Figure 8; Table C-1). During the spring 1998 season the mean CH_4 emissions as a function of ADG for steers grazing the E+ tall fescue pastures were higher than the mean emissions for steers grazing the other three pasture systems (Figure 8; Table C-1).

Cattle at the Holston Unit

Performance data

There were no differences between mean starting weights within an animal class (steers, cows, or calves) for any grazing season during 1997 and 1998 (Table A-2). Average body condition scores for cows grazing both pastures in 1997 were similar at the start of the spring season and at the end of the summer season, and were rated at about 5.5 on a scale ranging from 1 to 9.

Average daily gain was higher in spring 1997 than in summer 1997 for steers and cows grazing both pasture systems (Figure 9; Table A-2). Steer ADG was higher on the BMP pasture than on the UP in summer 1997 (Figure 9;

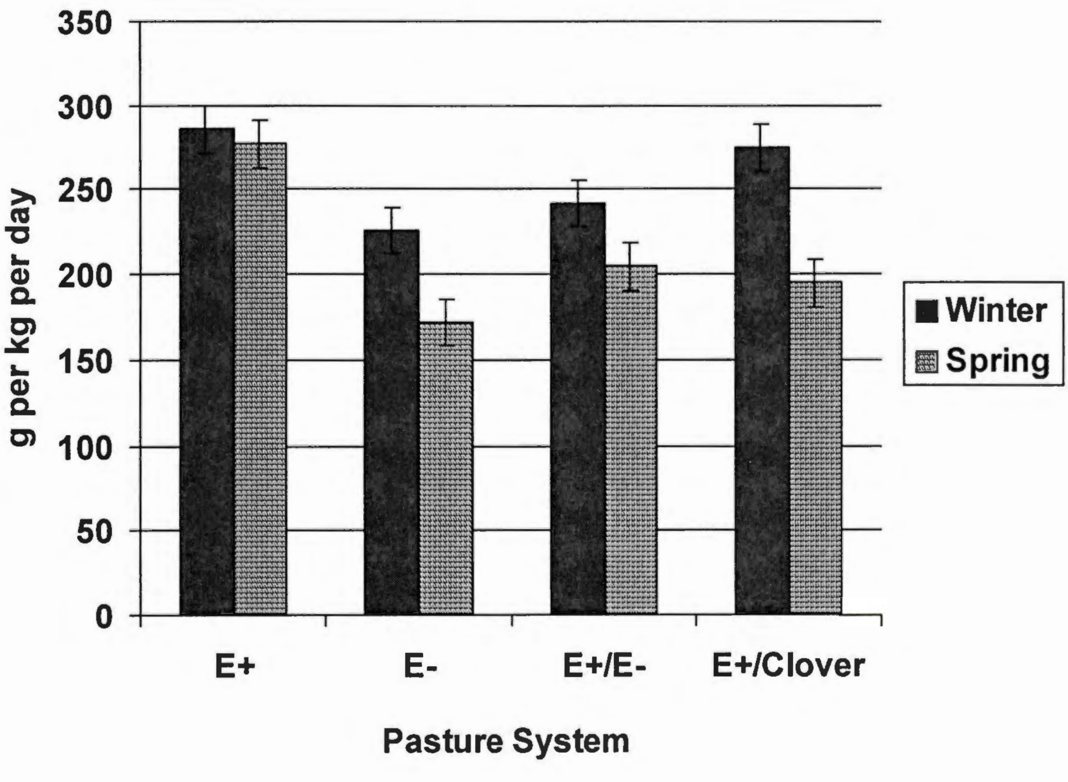

Figure 8. Least squares mean seasonal CH_4 emissions expressed as a function of ADG for steers grazing tall fescue pastures at the Blount Unit in 1998.

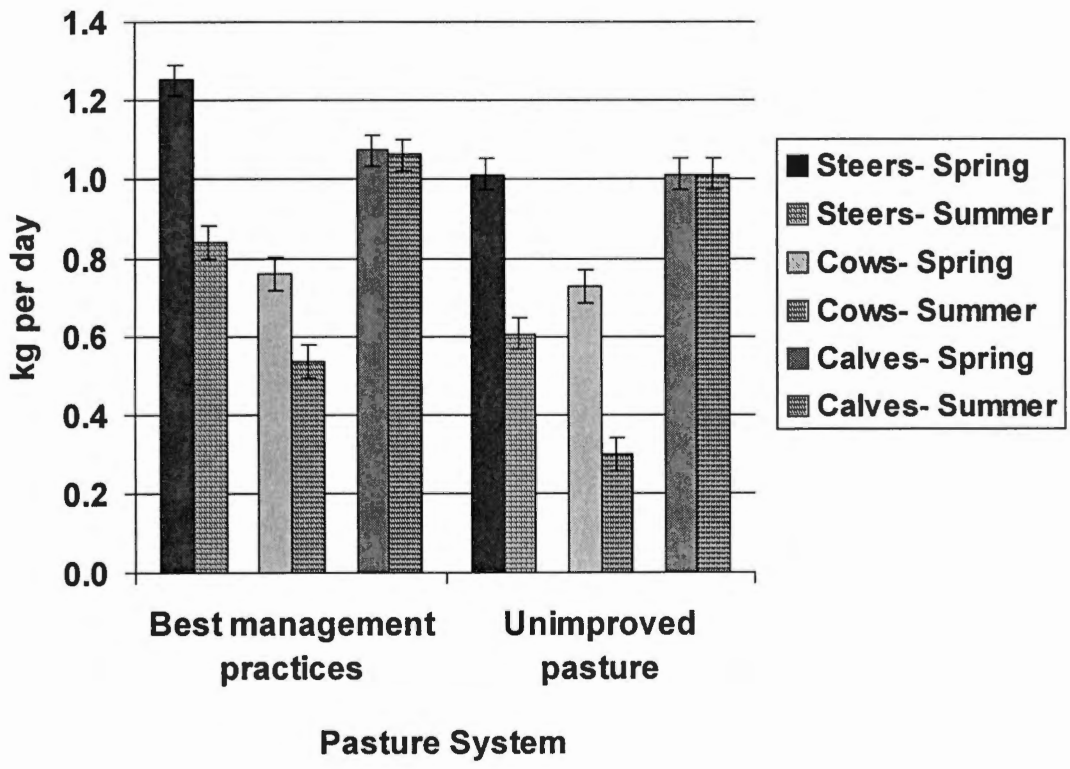

Figure 9. Seasonal ADG for cattle grazing tall fescue pastures at the Holston Unit in 1997.

Table A-2). While ADG for cows grazing both pasture systems decreased between the spring and summer of 1997, mean calf ADG did not differ between seasons or pasture systems (Figure 9; Table A-2). This indicated that as the spring and summer seasons progressed, the cows might have used intake energy and body reserves to provide enough milk for adequate calf growth.

Methane emissions

Mean daily CH_4 emissions did not differ between pasture systems for steers and cows in the spring and summer grazing seasons of 1997 (Figure 10; Table C-2). Cows had higher mean daily CH_4 emissions than steers during both spring and summer 1997 (Figure 10; Table C-2). However, when mean CH_4 emissions as a function of metabolic weight for cows and steers were compared, there were no differences between classes within a season (Figure 11; Table C-2). This observation is consistent with the findings of other researchers (Ferrell, 1988; Burrin et al., 1990) that body size is positively related to energy requirements and expenditures, as the cows were heavier than the steers (Table A-2).

The mean CH_4 emissions as a function of ADG were not different between cows and steers for the spring 1997 grazing season (Figure 12; Table C-2). Differences between mean CH_4 emissions as a function of ADG were observed during the summer 1997 grazing season. Cows grazing the UP emitted more CH_4 as a function of ADG than cows on the BMP pasture, and all cows emitted more than the steers on either pasture system (Figure 12; Table

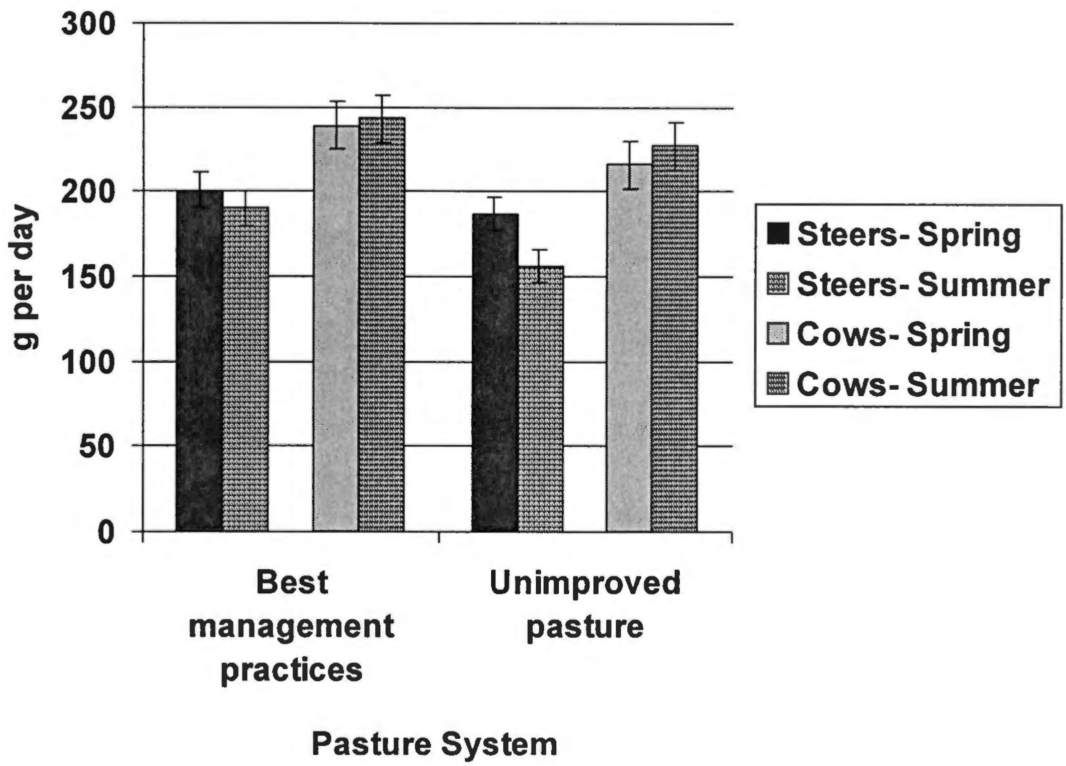

Figure 10. Least squares mean seasonal CH_4 emissions for cattle grazing tall fescue pastures at the Holston Unit in 1997.

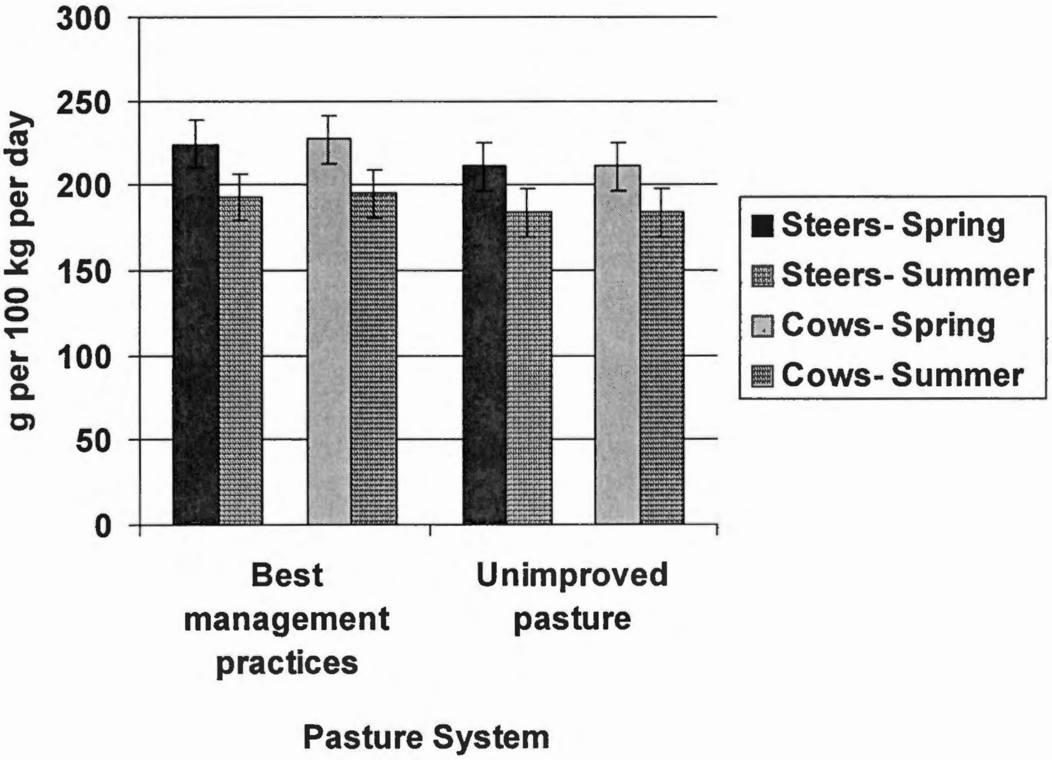

Figure 11. Least squares mean seasonal CH_4 emissions expressed in terms of metabolic weight per day for cattle grazing tall fescue pastures at the Holston Unit in 1997.

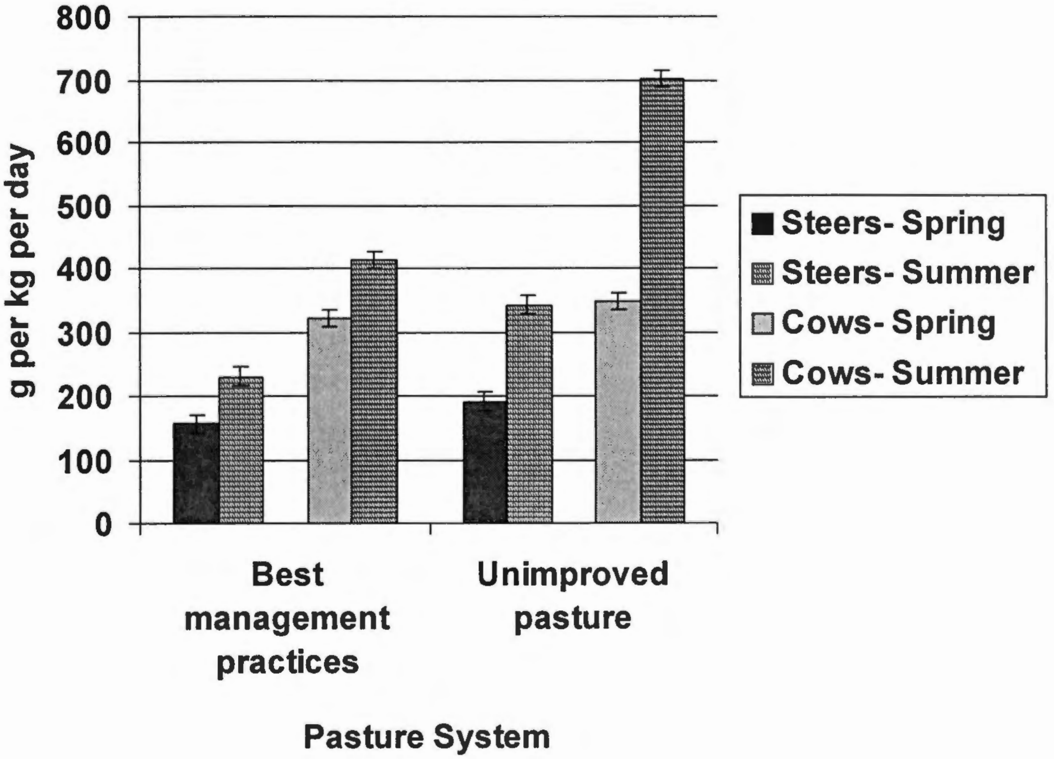

Figure 12. Least squares mean seasonal CH_4 emissions expressed as a function of ADG for cattle grazing tall fescue pastures at the Holston Unit in 1997.

C-2). Cows on the BMP pasture emitted a numerically larger amount of CH_4 as a function of ADG than the steers on both pasture systems (Figure 12). These findings indicated that the cows were less efficient than the steers when grazing either the BMP pasture or the unimproved pasture. The low efficiency of cows was related to the fact that the cows used intake energy to provide milk for calves rather than to increase their body weight. This was supported by the fact that the calves on the two pasture systems maintained the same ADG during both 1997 grazing seasons (Figure 12, Table A-2).

During the spring 1998 season steers grazing the BMP pasture emitted less CH_4 on a daily basis than the cows grazing the BMP pasture (Table C-3). When the mean CH_4 emissions were expressed as a function of metabolic weight, cows grazing the UP emitted less CH_4 than the cows grazing the BMP pasture and less than the steers grazing either pasture (Table C-3). Mean CH_4 emissions as a function of ADG were numerically higher for cows than for steers grazing both pasture systems during the spring 1998 season (Table C-3).

There were no differences detected between mean daily CH_4 emissions for steers within both the winter and spring 1998 seasons (Table C-4). Mean daily CH_4 emissions for steers grazing both pasture systems were higher in the spring than in the winter 1998 seasons (Table C-4). The same trends were observed for the mean steer CH_4 emissions as a function of metabolic weight during the winter and spring 1998 (Table C-4).

There were no differences between mean CH_4 emissions as a function of ADG for steers grazing the BMP pasture and the UP in the spring 1998 season

(Table C-4). Mean CH_4 emissions as a function of ADG for steers grazing the BMP pasture were lower than those for steers grazing the UP in the winter 1998 season (Table C-4). The steers grazing the UP were less efficient than the steers grazing the BMP pasture due to the numerically lower ADG for steers grazing the UP (Table A-2).

General discussion and implications

This study represents the first reports of daily CH_4 emissions from cattle grazing tall fescue pastures during winter, spring, and summer grazing seasons. The ranges of daily CH_4 emissions reported here for steers (about 100 - 200 $g{*}d^{-1}$) and for cows (about 150 - 240 $g{*}d^{-1}$) are consistent with the ranges reported by other researchers using the SF_6 tracer method (Johnson et al., 1994; McCaughey et al. 1997). Using prediction equation data, Crutzen et al. (1986) estimated that the total annual CH_4 production from cattle on range in the US would be about 54 kg per animal. The ranges of annual CH_4 emissions calculated from the ranges of daily emissions reported in this study are about 36 to 72 kg per animal for steers and about 54 to 86 kg per animal for cows.

When the CH_4 emission data were analyzed by year, the most significant effect was that of season. While there were instances where numerical differences were observed, statistical analysis was not able to detect such differences. This might possibly have been due to the lack of seasonal repetition in this study, as only the spring season observations were conducted in more than one year. Thompson et al. (1993) demonstrated the importance of including several years of data in pasture grazing studies to provide observations over a broad spectrum of environmental and climatic conditions. Indeed climatic factors were important during this study, for the Knoxville area experienced two consecutive springs with abnormally high precipitation levels. Elevated spring precipitation levels might have reduced the climatic stresses that pastures undergo during seasons with normal or below normal precipitation. In addition, it must be recognized that the number of animals from which the data presented here was limited.

In general, cows emitted more CH_4 per unit of animal produced than the steers. This might have resulted from an allocation of energy in the cows to milk production for their calves. Development of the rumen in calves depends on access to a fibrous diet and the availability of rumen microbes to inoculate the rumen (VanSoest, 1994). Developing calves are considered to be transitional ruminants at around 6 to 8 weeks of age, and to become functional ruminants at 8 to 12 weeks of age (Fahey and Berger, 1988). Therefore, the calves in this study could have been producing methane. Since that was not measured, the efficiency estimated for the cow-calf pair was incomplete. Further studies should investigate the efficiency of the cow-calf pair, rather than just that of the cow, since both contribute CH_4 to the environment. In addition, cows should be evaluated during the remainder of the year when choice of feeding managment usually results in positive weight gains for cows.

Differences in daily CH_4 production between E+ tall fescue pastures and improved pastures (E+ tall fescue/clover pastures and BMP pastures) were not observed. However, differences in CH_4 emissions as a function of ADG between

E+ tall fescue pastures and E+ tall fescue/clover pastures, and between the BMP pasture and the UP were observed, and were sometimes statistically different. Since less CH_4 was produced per unit of animal performance, pastures with better management practices were more efficient methane-wise than pastures receiving fewer management inputs.

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APPENDICES

APPENDIX A

PERFORMANCE DATA

Table A-1. Mean steer starting weight, season length, and ADG for animals grazing tall fescue pastures at Blount in 1997 and 1998.

Pasture system	1997[†]						1998					
	Spring			Summer			Winter			Spring		
	Weight	Season	ADG	Weight	Season	ADG	Weight	Season	ADG	Weight	Season	ADG
	kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$
E+	286^{a}	109	0.74^{ab}	352^{c}	63	0.49^{c}	256^{b}	154	0.39^{c}	316^{a}	113	0.54^{bd}
E-	297^{a}	109	0.95^{a}	383^{b}	63	0.54^{bc}	264^{b}	154	0.53^{bd}	346^{a}	113	0.90^{a}
E+/E-	289^{a}	109	0.90^{a}	356^{c}	63	0.51^{bc}	250^{b}	154	0.47^{bc}	323^{a}	113	0.62^{d}
E+/clover	290^{a}	109	0.88^{a}	387^{b}	63	0.75^{ab}	268^{b}	154	0.44^{bc}	337^{a}	113	0.78^{a}

[†] Least squares means for starting weight or ADG with the same superscript within the same year are not significantly different (P<.05).

Table A-2. Mean cattle starting weight, season length, and ADG for animals grazing tall fescue pastures at Holston in 1997 and 1998.

Pasture system	Animal class	1997†						1998					
		Spring			Summer			Winter‡			Spring		
		Weight	Season	ADG	Weight	Season	ADG	Weight	Season	ADG	Weight	Season	ADG
		kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$	kg	d	$kg{*}d^{-1}$
Best management practices	Steer	352^{c}	63	1.25^{d}	433^{d}	49	0.84^{bef}	279^{df}	141	0.36^{bc}	322^{ce}	106	0.84^{ab}
Unimproved pasture	Steer	355^{c}	63	1.01^{de}	420^{d}	49	0.61^{ab}	270^{ef}	141	0.28^{b}	301^{cd}	106	0.95^{a}
Best management practices	Cow	494^{a}	63	0.76^{abe}	550^{b}	49	0.54^{ac}	-	-	-	498^{b}	106	0.48^{ab}
Unimproved pasture	Cow	495^{a}	63	0.73^{ab}	546^{b}	49	0.30^{c}	-	-	-	535^{b}	106	0.51^{ab}
Best management practices	Calf	117^{e}	63	1.07^{df}	185^{f}	49	1.01^{df}	-	-	-	88^{a}	106	0.94^{ac}
Unimproved pasture	Calf	121^{e}	63	1.06^{de}	188^{f}	49	1.01^{df}	-	-	-	69^{a}	106	1.02^{a}

† Least squares means for starting weight or ADG with the same superscript within the same year are not significantly different (P<.05).
‡ Cow-calf pairs were not on the experimental pastures during the winter 1998 grazing season since the cows were calving during this time.

APPENDIX B

PRECIPITATION DATA

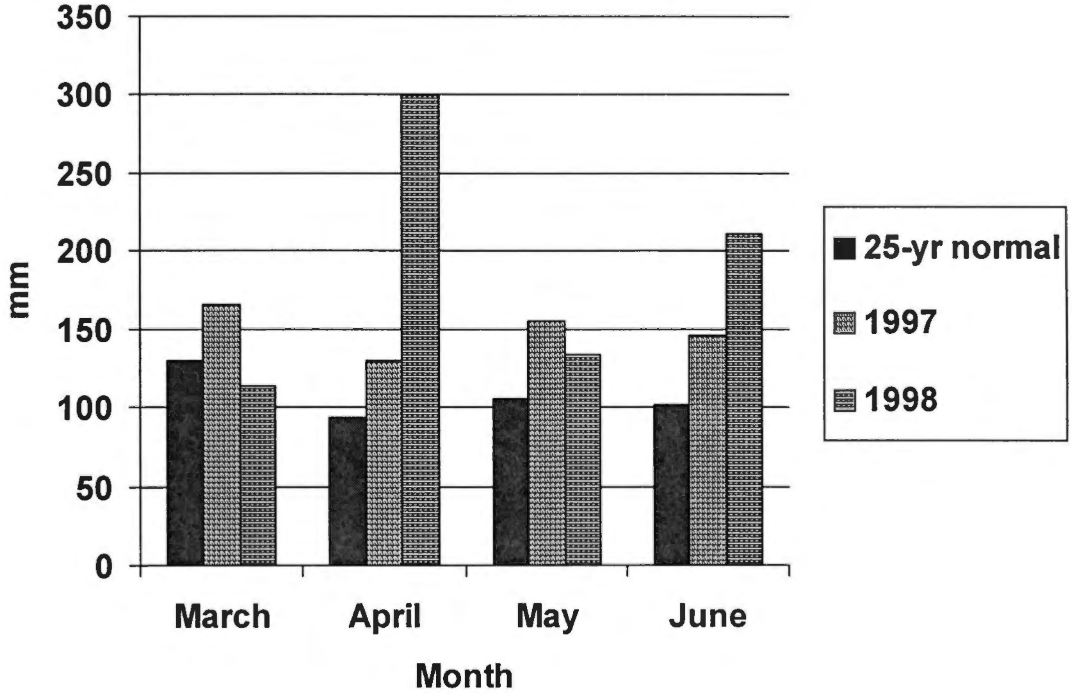

Figure B-1. Monthly spring precipitation for Knoxville, TN (NOAA, 1997; Knoxville Experiment Station, 1998, unpublished data).

APPENDIX C

METHANE EMISSION DATA

Table C-1. Mean seasonal CH_4 emission estimates per animal for steers grazing tall fescue pastures at Blount in 1997 and 1998.

Year	Pasture system	Daily CH_4		CH_4 as a function of ADG		CH_4 as a function of metabolic weight	
		Spring	Summer	Spring	Summer	Spring	Summer
		$g \cdot d^{-1}$ †		$g \cdot kg^{-1} \cdot d^{-1}$		$g \cdot 100\ kg^{-1} \cdot d^{-1}$	
1997							
	E+	166[ae]	148[fg]	223[ab]	306[cd]	212[abc]	178[d]
	E-	190[bc]	176[ad]	217[ab]	336[d]	232[b]	200[de]
	E+/E-	167[af]	154[eg]	179[a]	304[cd]	209[ac]	184[de]
	E+/clover	178[ab]	190[cd]	218[a]	265[bc]	220[ab]	213[abc]
		Winter	Spring	Winter	Spring	Winter	Spring
		$g \cdot d^{-1}$		$g \cdot kg^{-1} \cdot d^{-1}$		$g \cdot 100\ kg^{-1} \cdot d^{-1}$	
1998							
	E+	110[cd]	147[ab]	286[c]	277[c]	159[b]	179[a]
	E-	120[bcd]	153[a]	226[bd]	172[a]	164[ab]	165[ab]
	E+/E-	112[d]	127[abc]	242[cd]	205[ab]	160[ab]	151[ab]
	E+/clover	119[bcd]	154[a]	275[c]	195[ab]	165[ab]	174[ab]

† Least squares means for methane emissions in the same units, within the same year, with the same superscript are not significantly different ($P<.05$).

Table C-2. Mean seasonal CH_4 emission estimates per animal for cattle grazing tall fescue pastures at Holston in 1997.

Pasture system	Animal class	Daily CH_4		CH_4 as a function of ADG		CH_4 as a function of metabolic weight	
		Spring	Summer	Spring	Summer	Spring	Summer
		$g*d^{-1}$ †		$g*kg^{-1}*d^{-1}$		$g*100\ kg^{-1}*d^{-1}$	
Best management practices	Steer	201[de]	190[cd]	156[ab]	231[cef]	224[a]	193[cd]
Unimproved pasture	Steer	187[cd]	174[c]	191[ac]	342[be]	211[abc]	184[d]
Best management practices	Cow	239[a]	216[be]	322[abf]	413[ce]	227[a]	195[bcd]
Unimproved pasture	Cow	243[a]	227[ab]	347[abc]	702[d]	211[abc]	184[d]

† Least squares means for methane emissions in the same units with the same superscript are not significantly different (P<.05).

Table C-3. Mean seasonal CH_4 emission estimates per animal for cattle grazing tall fescue pastures at Holston in the spring grazing season of 1998.

Pasture system	Animal class	Daily CH_4	CH_4 as a function of ADG	CH_4 as a function of metabolic weight
		$g{*}d^{-1}$ †	$g{*}kg^{-1}{*}d^{-1}$	$g{*}100\ kg^{-1}{*}d^{-1}$
Best management practices	Steer	139[b]	166[bc]	170[b]
Unimproved pasture	Steer	145[ab]	141[b]	180[b]
Best management practices	Cow	168[a]	462[ac]	158[b]
Unimproved pasture	Cow	147[ab]	530[bc]	126[a]

† Least squares means for methane emissions in the same units with the same superscript are not significantly different (P<.05).

Table C-4. Mean seasonal CH_4 emission estimates per animal for steers grazing tall fescue pastures at Holston in 1998.

Pasture system	Daily CH_4		CH_4 as a function of ADG		CH_4 as a function of metabolic weight	
	Winter	Spring	Winter	Spring	Winter	Spring
	$g{*}d^{-1}$ †		$g{*}kg^{-1}{*}d^{-1}$		$g{*}100\ kg^{-1}{*}d^{-1}$	
Best management practices	94^{b}	140^{a}	402^{c}	167^{a}	127^{b}	170^{a}
Unimproved pasture	104^{b}	145^{a}	678^{b}	139^{a}	147^{b}	180^{a}

† Least squares means for methane emissions in the same units with the same superscript are not significantly different (P<.05).

VITA

Mitchell Adam Zuckerman was born on June 30, 1973 in Bronx, New York to Richard and Karen Zuckerman. He grew up in Fishkill, New York, and graduated from John Jay Senior High School in May 1991.

Mr. Zuckerman attended Binghamton University (State University of New York), where he received a Bachelor of Arts degree in Environmental Studies in May 1995. After working at the Institute of Ecosystem Studies in Millbrook, New York as a project assistant, he began working towards a Master's degree in Plant and Soil Sciences at the University of Tennessee, Knoxville in July 1996. He received his Master of Science degree in December 1998. Mr. Zuckerman will begin working towards a Doctoral degree in Ecology at the University of Georgia, Athens in August 1998.