Feeding condensed tannins to mitigate ammonia emissions from beef feedlot cattle fed high-protein finishing diets containing distillers grains^{1,2}

Karen M. Koenig,³ Karen A. Beauchemin, and Sean M. McGinn

Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB T1J 4B1, Canada

ABSTRACT: Two experiments were conducted to determine the effects of feeding a condensed tannin extract (CT) on dry matter intake (DMI), growth performance, carcass traits, and NH₃-N emissions of beef feedlot cattle fed high-protein barley-based finishing diets. In Exp. 1, 36 crossbred steers (346 ± 4.2 kg) were individually fed 4 diets with 20% corn dried distillers grains (DG) and increasing concentrations of a CT extract from *Acacia mearnsii* (black wattle) at 0%, 1.2%, 2.4%, and 3.5% of DM (9 steers per diet) for 52 d. The DMI was not affected at 1.2% and 2.4% but tended ($P = 0.08$, quadratic effect) to decrease at 3.5% CT extract. There was no effect ($P \geq 0.12$) of increasing CT extract on ADG, but G:F tended ($P = 0.09$) to decrease linearly. In Exp. 2, 148 crossbred steers (457 ± 3.8 kg) were allocated to 16 pens with 4 pens per treatment in a completely randomized design and fed for 83 d. The 4 dietary treatments included 0% corn DG (0DG), 20% DG (20DG), 40% DG (40DG), and 40% DG with 2.5% CT extract (40DGCT) and contained 13.3, 15.9, 20.4, and 19.4% CP, respectively. All cattle were weighed, and blood was collected from 5 steers per pen every 3 wk. Ammonia emissions were measured in four 3-wk periods using the integrated

horizontal flux technique with passive NH₃ samplers from 2 pens of cattle fed 0DG and 20DG (Period 1), 40DG and 40DGCT (Period 2), 0DG and 40DG (Period 3), and 0DG and 40DGCT (Period 4). There was no effect ($P \geq 0.15$) of diet on final body weight (621 ± 7.1 kg), DMI (11.9 ± 0.25 kg/d), ADG (1.98 ± 0.07 kg/d), G:F (166 ± 5.4 g/kg), and carcass traits. Plasma urea N (PUN) increased ($P < 0.001$) from 0DG to 40DG (113 to 170 ± 6.0 mg N/L) and was reduced ($P < 0.001$) by 40DGCT (146 mg N/L) compared with 40DG and tended ($P = 0.09$) to be reduced compared with steers fed 20DG (153 mg N/L). Ammonia-N emissions were greater from cattle fed 40DG [113.7 vs. 70.8 ± 4.57 g N/(steer·d), $P = 0.003$] and tended to be greater from cattle fed 20DG [51.3 vs. 26.3 ± 11.2 g N/(steer·d), $P = 0.11$] compared with 0DG. Cattle fed 40DGCT tended to have lower NH₃-N emissions compared with cattle fed 40DG [72.7 vs. 95.1 ± 9.3 g N/(steer·d), $P = 0.09$ and 20.5 vs. 26.5 ± 2.64% N intake, $P = 0.11$]. Feeding 2.5% CT to beef feedlot cattle fed a high-protein diet had no detrimental effect on performance, reduced PUN indicating lower urinary urea N excretion, and lowered NH₃-N emissions by 23%.

Key words: ammonia, condensed tannins, corn distillers grains, feedlot cattle, growth performance

© Crown copyright 2018. This article contains public sector information licensed under the Open Government Licence v3.0 (<http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>).

J. Anim. Sci. 2018.96:4414–4430
doi: 10.1093/jas/sky274

¹The study was supported in part by the Alberta Livestock and Meat Agency Ltd., Edmonton, AB, and Agriculture and Agri-Food Canada, Lethbridge, AB. The authors gratefully acknowledge the technical contribution provided by B. Farr, R. Roth, K. Andrews, T. Coates, and D. Vedres and the animal care and handling by the support staff of the Beef Research Feedlot Unit of Agriculture and Agri-Food Canada.

²Lethbridge Research and Development Centre contribution number 38718046.

³Corresponding author: karen.koenig@agr.gc.ca

Received May 10, 2018.

Accepted July 3, 2018.

INTRODUCTION

Livestock production plays a critical role in achieving food security; however, livestock farming systems are major emitters of reactive nitrogen (N). Reactive forms of N include inorganic forms such as NH_3 , nitrous oxide, nitrogen oxides, nitrate, and organic forms such as urea and amines. Ammonia is of concern because it can form secondary products in the atmosphere contributing to fine particulate matter and reduced air quality and when deposited can increase the risk of acidification and eutrophication of natural ecosystems (Hristov et al., 2011). Agriculture contributes to over 80% of the North American NH_3 emission inventories and animal agriculture accounts for over 65% of agricultural emissions (USEPA, 2014; ECCC, 2016).

With the expansion of the renewable energy sector, the North American Ethanol Industry is now one of the largest contributors to the global animal feed supply (Renewable Fuels Association, 2017). Distillers grains, the major by-product feeds from grain-based ethanol production, are an economic energy source and are replacing approximately 15% to 50% of traditional grains in the ration (Klopfenstein et al., 2008). However, N and P in distillers grains are 3 times the concentration of the parent grain, and as a result, protein and P requirements of cattle are routinely exceeded. Nitrogen fed in excess of requirements is excreted largely as urea N which is readily converted by microbial urease enzyme to NH_3 .

Condensed tannins (CT) are complex polyflavonoid compounds found in forage, browse, and legume species with an affinity to bind proteins and to a lesser extent polysaccharides and minerals (Hagerman and Butler, 1981; Waghorn et al., 1994; Halvorson et al., 2017). The nature and dietary concentration of CT contribute to the beneficial and adverse nutritional and physiological effects in ruminants (Mueller-Harvey, 2006; Waghorn, 2008; Tedeschi et al., 2014). The objective of this study was to determine the effect of feeding a CT extract on intake, growth performance, carcass traits, and NH_3 -N emissions of feedlot cattle fed high-protein finishing diets containing distillers grains. The hypothesis was that feeding the CT extract would reduce the susceptibility of excess feed N excreted in manure to loss as NH_3 -N without negatively affecting growth performance of feedlot cattle.

MATERIALS AND METHODS

The study was conducted at Agriculture and Agri-Food Canada's Lethbridge Research and Development Centre (AB) in the Individual

Feeding Barn and the Beef Research Feedlot. The cattle originated from the Centre's Onefour grazing pasture substation. Animals were cared for according to the guidelines of the [Canadian Council on Animal Care \(2009\)](#). Experimental procedures involving animals were approved by the Institutional Animal Care and Use Committee at the Lethbridge Research and Development Centre.

Experiment 1. Increasing Dietary Tannin Concentration and Feed Intake

In the first experiment, the effect of feeding increasing concentrations of CT extract on DMI of beef steers was investigated. The highest dietary CT extract concentration with no adverse effect on DMI was then selected for further evaluation of its effects on growth performance and NH_3 -N emissions in Exp. 2.

Thirty-six Angus-crossbred steers (346 ± 4.2 kg) were used in a 52-d experiment designed as a completely randomized design with 4 dietary treatments (9 animals per treatment). The steers were housed in individual pens measuring 1.85×6.15 m, with a feed bunk and water trough, and bedded with straw in a sheltered unheated barn. Steers were weighed on 2 consecutive days prior to feeding, stratified by mean BW, and randomly allocated to the 4 treatments to equalize initial BW among treatments. The steers had ad libitum access to feed and water throughout the study. The treatments were CT extract powder from *Acacia mearnsii* (Black wattle, Weibull Black, Tanac SA, Montenegro, Brazil) at 0%, 1.2%, 2.4%, and 3.5% (DM basis) of the total mixed ration (TMR). The extractable CT concentration of the *A. mearnsii* extract powder determined by the butanol/HCl procedure was 53.0% (DM basis). The CT extract was added to the TMR daily at the time of mixing in a Data Ranger (American Calan, Northwood, NH).

Cattle were transitioned from a backgrounding diet composed of 48% whole crop barley silage, 45% steam-rolled barley grain, and 7% supplement containing protein, minerals, and vitamins to a finishing diet containing 67% temper-rolled barley grain, 20% corn dried distillers grains and solubles (DG), 8% barley silage, and 5% supplement in 4 steps over a 21-d period. In addition, the cattle were also adapted to increasing dietary concentrations of the CT extract. Cattle assigned to the 1.2, 2.4, and 3.5% CT treatments were fed 0.6% CT during the 21-d transition to the finishing diet and then the CT was increased in 0.6% increments at 4- to 7-d intervals until all cattle were fed the CT concentration of

their assigned treatments (at day 42). Cattle were fed their treatment diets for an additional 10 d (to day 52). The TMR were offered once daily in an amount to permit ad libitum intake (5 to 10% orts). The weight of feed allocated to each animal was recorded daily.

Samples of the TMR were collected during each step of the 21-d transition to the finishing diet, each 4- to 7-d interval corresponding to the duration that each increasing level of CT was fed, and twice during the last 10 d when all cattle were fed their respective treatment diet. Orts were collected and weighed in a feed cart with a scale system (Model 1015, Avery Weigh-Tronix, Fairmont, MN) daily and combined for each animal and diet. Samples of the TMR and orts were dried at 55 °C in a forced draft oven for 48 h to determine DM content and compute DMI. Dried samples of the basal finishing TMR (0% CT) for each interval and the last 10 d (for a total of 6 samples) were ground using a cutter mill through a 4-mm-diameter screen and then through a 1-mm-diameter screen (model 4 Wiley mill, Thomas Scientific, Swedesboro, NJ), combined and stored at ambient temperature until chemical analysis [DM, OM, CP, NDF, ADF, and starch]. Cattle were weighed prior to feeding and at the same time of day on 1 d at the beginning and end of the 21-d transition period and weekly thereafter. On day 52 at the time of weighing, blood was collected from all cattle via puncture of the jugular vein into sterile evacuated tubes containing an anticoagulant (10 mL, lithium heparin, Vacutainer, Becton Dickinson, Oakville, ON) and centrifuged at $3,000 \times g$ and 4 °C for 20 min. The plasma was transferred to individual vials and stored at -20 °C until analysis of plasma urea N (PUN) as an indicator of protein status of the cattle.

Experiment 2. Growth Performance and Ammonia Emissions

Animals and housing. A total of 148 Angus-cross steers (425 ± 4.3 kg, initial BW) were used in a 97-d feedlot experiment from 30 March to 15 July (14 d for adaptation to diets and 83 d for conduct of the experiment). Steers were individually weighed (Cattlelac Hydraulic Squeeze with 4 load cells, Red Deer, AB and Cardinal Detecto 758 Indicator, Cardinal Scale Manufacturing Co., Webb City, MO) before feeding, stratified according to BW, allocated to 16 pens of 9 or 10 animals each, and then 4 pens were randomly assigned to each of the 4 dietary treatments. At the time of weighing, steers were implanted with a commercial growth

promotant (120 mg of trenbolone acetate USP and 24 mg of estradiol USP, Component TE-S, Elanco Animal Health, Guelph, ON). Steers were housed in open-air pens measuring 14×19.5 m with soil-surfaced floors, 12-m fence-line concrete feed bunk, 1.65-m concrete apron, an automatic continuous flow water bowl, and wind break fencing. Each pen had a straw-bedded rest area away from the feed bunk. The health of the cattle was monitored daily by visual observation. Cattle showing signs of injury or disease were treated and returned to the pen. Cattle with persistent health problems were removed from the experiment. Two steers were removed from the feedlot trial due to health issues. One of the steers (fed the 40DG diet) died as a result of bloat and a second steer (fed the 40DGCT diet) was removed due to an injury to the shoulder. Data for these animals were removed from the data set.

Dietary treatments. The 4 dietary treatments (Table 1, DM basis) included control (no corn DG, 0DG), 20% corn DG (20DG), 40% corn DG (40DG), and 40% corn DG with 2.5% CT extract (40DGCT) from *A. mearnsii* (Weibull Black, Tanac SA; the same lot as Exp. 1). The control diet contained 9% whole crop barley silage, 86% temper-rolled barley grain, and 5% supplement. The corn DG and CT extract were substituted for barley grain. Diets were formulated to meet the mineral and vitamin requirements for beef cattle (NRC, 2000). The 20DG dietary treatment provided a CP concentration intermediate to the 0DG and 40DG and a midpoint reference for assessing the extent of the relative effects of feeding 40DG with and without the CT extract. Steers assigned to the 0DG, 20DG, and 40DG were adapted from a diet containing 82% barley grain-based concentrate and 18% barley silage (DM basis) to the experimental diets containing 91% concentrate with either 0, 20, or 40% corn DG and 9% barley silage by feeding a series of 3 diets with increasing proportions of concentrate and DG for 14 d prior to the start of the experiment. Steers assigned to the 40DGCT dietary treatment were adapted to the increased proportion of concentrate, DG and CT by feeding a series of 5 diets for the 14 d with a 0.5% unit increase in CT with each step.

The diets were mixed daily and delivered to the feed bunks using a feed mixer (Beck 220, Beck Industries, Lethbridge, AB, with Weigh-Tronix RD712 scale system, Fairmont, MN) and fed as a TMR once per day between 1000 and 1100 h. The amount of feed offered was based on visual assessment of the bunk before feeding and adjusted as

Table 1. Ingredients and nutrient composition of the dietary treatments

Item	Diets ¹			
	0DG	20DG	40DG	40DGCT
Ingredient, % of DM				
Barley silage ²	9.0	9.0	9.0	9.0
Barley grain, temper-rolled ³	86.0	66.0	46.0	43.5
Corn dried distillers grains and solubles ⁴	—	20.0	40.0	40.0
Tannin extract (<i>Acacia mearnsii</i>) ⁵	—	—	—	2.50
Supplement ⁶				
Barley grain, ground	3.30	3.30	3.30	3.30
Calcium carbonate	1.35	1.35	1.35	1.35
Salt	0.162	0.162	0.162	0.162
Trace mineral and vitamin mix ⁷	0.054	0.054	0.054	0.054
Vitamin E (500,000 IU/kg)	0.006	0.006	0.006	0.006
Rumensin premix ⁸	0.017	0.017	0.017	0.017
Molasses	0.105	0.105	0.105	0.105
Flavoring agent ⁹	0.003	0.003	0.003	0.003
Nutrient composition ¹⁰ , % of DM				
DM (% as fed)	90.4 ± 0.55	92.7 ± 0.98	90.9 ± 0.48	92.8 ± 0.10
OM	96.0 ± 0.36	95.2 ± 0.54	95.2 ± 0.42	94.9 ± 0.33
CP	13.3 ± 0.66	15.9 ± 0.71	20.4 ± 0.48	19.4 ± 0.50
Starch	53.2 ± 3.45	44.7 ± 4.47	33.4 ± 1.60	32.2 ± 1.01
NDF	18.5 ± 1.63	21.8 ± 1.18	25.7 ± 0.36	24.9 ± 1.24
ADF	7.39 ± 0.43	8.21 ± 0.33	10.5 ± 0.29	10.2 ± 0.56
Crude fat	2.51 ± 0.24	3.88 ± 0.08	5.55 ± 0.37	5.51 ± 0.13
GE, MJ/kg	19.0 ± 0.23	19.6 ± 0.48	20.6 ± 0.25	21.2 ± 0.60

¹0DG = no corn dried distillers grains and solubles (DG), 20DG = 20% of diet DM as DG, 40DG = 40% of diet DM as DG, 40DGCT = 40% of diet DM as DG and 2.5% of diet DM as condensed tannin extract of *Acacia mearnsii*.

²Contained on a DM basis: 38.7 ± 1.73% DM, 92.6 ± 0.48% OM, 10.8 ± 0.46% CP, 24.2 ± 0.82% starch, 43.8 ± 0.97% NDF, 26.1 ± 0.91% ADF, 2.86 ± 0.16% crude fat, and 21.7 ± 0.23 MJ/kg GE. Particle size distribution of the silage using the Penn State Particle Separator = 4.79 ± 0.54% > 19.0 mm, 47.1 ± 3.64% 19.0 to 8.0 mm, 45.7 ± 3.6% 8.0 to 1.18 mm, and 2.37 ± 0.71% < 1.18 mm.

³Contained on a DM basis: 85.4 ± 0.94% DM, 97.7 ± 0.30% OM, 13.5 ± 0.81% CP, 59.5 ± 0.93% starch, 17.6 ± 1.51% NDF, 5.64 ± 0.18% ADF, 2.17 ± 0.18% crude fat, and 18.6 ± 0.47 MJ/kg GE. The bushel weight of whole barley was 66.5 ± 3.05 kg/hL (53.0 ± 2.30 lb/Winchester bu) and the processing index of the temper-rolled barley was 74.3 ± 4.40%.

⁴Contained on a DM basis: 92.0 ± 0.13% DM, 95.5 ± 0.27% OM, 31.2 ± 0.65% CP, 5.64 ± 0.52% starch, 34.4 ± 0.96% NDF, 14.2 ± 1.01% ADF, 11.48 ± 0.52% crude fat, and 22.3 ± 0.14 MJ/kg GE.

⁵Weibull Black, Tanac SA, Montenegro, Brazil.

⁶Ingredients of the supplement were pelleted [0.34 cm (1/4 in) diameter].

⁷Lethbridge Research and Development Centre Feedlot Premix provided per kg of diet DM: 55 mg/kg of Zn, 14 mg/kg of Cu, 25 mg/kg of Mn, 0.6 mg/kg of I, 0.27 mg/kg of Se, 0.2 mg/kg of Co, 9,200 IU/kg of vitamin A, 460 IU/kg of vitamin D, and 13 IU/kg of vitamin E.

⁸Contained monensin (as monensin sodium) at 200 g/kg of premix (DM basis), Elanco Animal Health, Guelph, ON.

⁹Anise 422 powder; Canadian Bio-Systems Inc., Calgary, AB.

¹⁰Mean ± SD, *n* = 4 periods.

necessary to allow for a minimum of 5 to 10%orts to permit ad libitum consumption. The weight of the feed delivered to each pen was recorded daily.

Samples of the barley silage (approximately 10-L volume from the face of the pit), temper-rolled barley grain, corn DG and supplements (2 to 4 L each from the storage bins), and TMR (approximately 4 L from the mixer wagon after the second pen was fed) were collected once a week. Samples were reduced in size using a riffle splitter. A subsample (approximately 1 L) was dried at 55 °C in a forced draft oven for 48 h to determine DM content. The DM content of the silage, grain, and supplements

was used to adjust the ingredient proportions of the diet when the DM of the barley silage deviated more than 3% from the mean DM percentage. A second subsample of each of the feeds and diets was combined by period and frozen (−20 °C) until the end of the period when it was thawed, split, and dried at 55 °C. The dried subsamples were ground as described for Exp. 1 to pass through a 1-mm-diameter screen (model 4 Wiley mill, Thomas Scientific) and stored at approximately 20 °C until analysis. Particle size distribution of an additional subsample of the barley silage that was combined by period, thawed and split was determined using

the Penn State Particle Separator with 3 sieves with apertures of 19.0, 8.0, and 1.18 mm (Lammers et al., 1996, as modified by Kononoff et al., 2003). Samples of whole and temper-rolled barley grain were collected from the Centre's Feed Mill as each 1-t batch was processed (approximately weekly and averaged for each period) to determine the processing index. The processing index was defined as the volume weight of the grain after processing divided by the volume weight of the whole barley grain before processing $\times 100\%$ (DM basis; 0.5 L cup, Seedburo, Chicago, IL). Samples of the CT extract were collected from each 25-kg bag that was opened and combined for each period. Orts were removed from the feed bunks at the end of each 3-wk period (on the same day that steers were weighed), and then reduced in size, dried, and ground as described for the feed samples.

Growth performance. Steers were weighed individually on 2 consecutive days at the start (pen assignment was based on BW measured on the first day) and end of the experiment and on 1 day after adaptation and at successive 3-wk intervals until the end. Cattle were weighed at the same time of day (between 0800 and 1000 h) and before the delivery of fresh feed. Body weights were adjusted and reported on a 4% shrunk weight basis (NRC, 2000) to account for gut fill. Five steers were randomly selected from each pen on each treatment and blood samples were collected from the same cattle when weighed every 3 wk. Blood was collected via puncture of the jugular vein into evacuated tubes (10 mL, Vacutainer Lithium Heparin, Becton Dickinson) and processed and stored as described for Exp. 1 for analysis of PUN.

Dry matter intake (kg/d for each period) was calculated as follows: $\{[\Sigma \text{feed offered daily (kg/d)} \times \% \text{DM}_{\text{TMR}}] - [\text{orts (kg)} \times \% \text{DM}_{\text{orts}}]\} \div (\text{number of steers} \times \text{number of days in each period})$. The ADG for individual steers was determined as the coefficient of the linear regression relationship between BW as the dependent variable and time as the independent variable (ADG_{Reg}). The ADG was also calculated for each animal in each period by subtracting initial BW from the final BW (shrunk) and dividing by the number of days in the period. Feed conversion efficiency (G:F) was calculated for each period as grams of ADG per kilogram of DMI.

Steers (from 12 of the 16 pens) were transported in 2 groups on 2 consecutive days (the fourth and fifth day after the last measurement of BW) approximately 210 km to a federally inspected commercial abattoir (XL Beef, Calgary, AB) for slaughter and

carcass trait evaluation. Carcasses were inspected, chilled for 24 h, and complete Canadian grade data were collected by an accredited grader of the Canadian Beef Grading Agency according to the Canadian livestock carcass grading regulations (Canadian Food Inspection Agency, 2012). Measurements included longissimus muscle area, grade fat thickness, average fat thickness, marbling score, lean meat yield, and Canadian quality grade. Dressing percentage was calculated as the hot carcass weight divided by the final shrunk BW before shipping. Carcass evaluation was not measured on the 4 pens of cattle that were used in the isolated pens for $\text{NH}_3\text{-N}$ emission measurement.

Ammonia-N emissions. The simultaneous measurement of $\text{NH}_3\text{-N}$ emissions from cattle fed the dietary treatments each period was limited by having only 2 isolated pens. For every 3-wk period, 2 pens of cattle were moved from their Research Feedlot pens to the 2 isolated pens for the measurement of $\text{NH}_3\text{-N}$ emissions. Emissions were measured from 1 pen of cattle fed 0DG and 20DG, 40DG and 40DGCT, 0DG and 40DG, and 0DG and 40DGCT during periods 1, 2, 3, and 4, respectively. Therefore, there was no replication of the experimental units (pen) for the $\text{NH}_3\text{-N}$ measurement technique in each period. The $\text{NH}_3\text{-N}$ emission measured on each experimental unit (pen) was replicated for 4 consecutive 24-h periods within each 3-wk period.

The isolated pens were located 200 m south of the Research Feedlot to minimize background $\text{NH}_3\text{-N}$ and were orientated on a north-south and east-west axis with unobstructed wind flow and separated from each other by 30 m. Each pen measured 14×18 m with soil-surfaced floors, 9-m fence-line concrete bunk, and an automatic continuous flow water bowl. For each period, the isolated pens were scraped of manure and bedded with straw (1 large square bale per pen; approximately 325 kg DM) before movement of steers into the pens.

The steers remained in the isolated pens for 14 d to permit the formation of a manure pad before measurement of $\text{NH}_3\text{-N}$ emissions. Ammonia-N emissions were then measured from each pen for 4 consecutive 24-h periods using the integrated horizontal flux technique with passive NH_3 sampler units (Schjoerring et al., 1992; Sommer et al., 1996; McGinn and Sommer, 2007) as described and modified by Koenig et al. (2013). This technique combines the measurement of vertical profiles of $\text{NH}_3\text{-N}$ accumulated in the passive sampler units with wind speed and direction to compute $\text{NH}_3\text{-N}$ emission from each pen. Sampler tubes were

mounted horizontally to a vertical mast at heights of 0.5, 1, 2, and 3 m located in the middle of the north, south, east, and west perimeters of each of the pens. The NH_3 from the atmosphere enters the tubes and reacts with the dry oxalic acid to form NH_4 oxalate. After each 24-h period of exposure, the samplers were removed from the masts, disassembled, and the glass tubes immediately capped and placed in NH_3 -free airtight container. The NH_4 oxalate of each glass tube was dissolved in 5 mL of deionized water and the extract analyzed for NH_3 -N. Meteorological instrumentation was located adjacent to the pens. Wind speed was measured at the same heights as the samplers (i.e., 0.5, 1, 2, and 3 m) and wind direction at 3 m (WINDCAP Ultrasonic Wind Sensors WS425, Vaisala, Helsinki, Finland). The meteorological data were recorded every 5 s and averaged for 30-min intervals by a data logger (CR23X, Campbell Scientific, Inc., Logan, UT). In addition, air temperature (HMP35C, Campbell Scientific, Logan, UT) at 2 m and rainfall were measured at the Centre's weather station (Lethbridge CDA, 49°41'42 N, 112°46'03 W). The vertical net flux of NH_3 -N for each 24-h collection was determined as described by Koenig et al. (2013).

On day 11 of each period and 2 to 3 h after feed allocation, rumen fluid samples (approximately 100 mL) were collected via an oral ruminal probe connected to a vacuum pump from each of the 10 steers from each of the isolated pens. Ruminal fluid was strained through 4 layers of cheesecloth, and then, ruminal pH was measured immediately using a pH meter. Five milliliters of the ruminal fluid filtrate was combined with 1 mL of 0.2 M H_2SO_4 , and another 5 mL of the filtrate was combined with 1 mL of 25% wt/vol meta-phosphoric acid and stored at -20°C until analysis of NH_3 -N and VFA concentrations, respectively.

Chemical Analysis

Dry matter of samples was determined by drying at 135°C for 2 h (AOAC, 2016, method no. 930.15) followed by hot weighing and used to correct chemical results to DM basis. The OM content was calculated as the difference between 100 and the percentage ash (AOAC, 2016, method no. 942.05). The NDF was determined based on the procedure of AOAC (2016, method 2002.04) using heat-stable α -amylase (Termamyl 120 L, Type L, Novozymes A/S, Bagsvaerd, Denmark) and sodium sulfite, and ADF was determined according to AOAC (2016, method 973.18) with

modifications to each procedure for use in an ANKOM Fiber Analyzer (ANKOM Technology Corp., Fairport, NY). Samples previously ground through a 1-mm-diameter screen were further ground using a ball mill (Mixer Mill MM2000, Retsch, Haan, Germany) to a fine powder for determination of starch and N. Starch was determined by enzymatic hydrolysis of α -linked glucose polymers as described by Koenig et al. (2013). Nitrogen was quantified by flash combustion with gas chromatography and thermal conductivity detection (AOAC, 2016, method no. 990.03; Carlo Erba Instruments, Milan, Italy). The CP was calculated as $\text{N} \times 6.25$. Samples of the major feed ingredients and the TMR for the 4 periods were combined to make one representative sample each for crude fat analysis. Crude fat was determined by ether extraction for 6 h (AOAC, 2016, method no. 920.39; E-816 Hot Extraction Unit, Buchi Labortechnik AG, Flawil, Switzerland). Gross energy was determined using a dry static jacket isothermal bomb calorimeter (E2K Isothermal Bomb Calorimeter, Digital Data Systems, Pty. Ltd., Gauteng, South Africa). The CT concentration was determined in the *A. mearnsii* extract using the butanol/HCl assay with reference standards prepared from the purified extract (Hagerman, 2002). Plasma was analyzed for PUN by reaction with diacetyl monoxime and colorimetric detection using a flow analyzer (Method A332, Astoria 2 Analyzer, Astoria Pacific, Inc., Clackamas, OR). Ammonia-N was determined in the extracts from the air sampling tubes and ruminal fluid using the salicylate method (Kempers and Zweers, 1986). Volatile fatty acid concentrations in ruminal fluid were quantified using crotonic acid as an internal standard by GLC (Model 5890; Hewlett Packard, Little Falls, DE) with a capillary column (30 m $\times$ 0.25 mm internal diameter, 1 mm phase thickness, bonded PEG, Supelco Nukol; Sigma-Aldrich Canada, Oakville, ON, Canada) and flame ionization detection.

Statistical Design and Analysis

Data of Exp. 1 and 2 were analyzed as completely randomized designs using a mixed linear model (Release 9.3; SAS Inst., Inc., Cary, NC). The restricted maximum likelihood method was used for estimating variance components, and the Kenward–Roger option was used to adjust the degrees of freedom. The model for DMI during adaptation to the CT treatments in Exp. 1 included the concentration of CT in the diet, the 4- to 7-d step (as a repeated measure), and the diet

× step interaction as fixed effects, and animal as a random effect and the experimental unit. For the repeated measures model, the variance and covariance error structures that were investigated included the compound symmetry and heterogeneous compound symmetry. The error structure with the lowest Akaike information criteria fit statistic was selected for the model. Differences among treatments were determined using Fisher's protected ($P \leq 0.05$) LSD test using the PDIFF option. The SLICE option was used when the diet × time interaction was significant to partition and test the simple main effects. The model for the data of Exp. 1 for BW, DMI, ADG, G:F, and PUN for the last 10 d of the experiment when all animals were on their respective dietary treatments included the concentration of CT extract in the diet as a fixed effect and animal as the experimental unit. Linear and quadratic effects of the increasing dietary concentration of CT were examined using contrast statements.

Data of Exp. 2 for initial BW, final BW, ADG_{Reg} , carcass traits (except quality grade), and ruminal fermentation characteristics for each animal were analyzed with a model that included diet as a fixed effect and pen and animal within pen as random effects. Pen was the experimental unit. Data for DMI for each pen, ADG, G:F, and PUN for each animal for each 3-wk period were analyzed with a model with the fixed effects of diet, period as a repeated measure, and diet × period interaction and the random effects of animal within pen. Pen was the experimental unit. The variance and covariance error structures selected and evaluated were as described earlier. Quality grade was analyzed by the

frequency procedure using the chi-square option. The data for NH_3 -N emissions for each of the 4 d from the 2 isolated pens for each period were analyzed using pairwise *t*-test where the measurements from each pen were paired by day. Differences were considered significant at $P \leq 0.05$, and trends were discussed at $0.05 < P \leq 0.10$ for all data except for the NH_3 -N emission data where trends were discussed at $0.05 < P \leq 0.12$.

RESULTS

Experiment 1. Increasing Dietary Tannin Concentration and Feed Intake

The basal finishing TMR with 20% DG (0% CT) averaged $77.8 \pm 1.86\%$ DM and contained (DM basis) 94.6% OM, 14.9% CP, 19.1% NDF, 7.13% ADF, and 43.3% starch.

Initial BW at the start of the experiment did not differ ($P = 0.13$) among cattle assigned to the dietary treatments and averaged 346 ± 4.2 kg/d (Table 2). There was, however, a tendency ($P = 0.08$) for the increasing dietary concentration of CT to linearly decrease final BW at day 52. During the stepwise adaptation of the steers to their dietary treatments, there was an interaction between diet × time ($P = 0.005$) due to differences in DMI among the intervals within each CT treatment, although there were no differences ($P > 0.10$) in DMI among steers fed the CT treatments at each interval (Fig. 1). When DMI was averaged over the last 10 d of the experiment, when all steers were fed their respective diets, there was a

Table 2. Feed intake and performance of beef feedlot cattle individually fed increasing concentrations of condensed tannins in a barley-based finishing diet with 20% corn distillers grains

Item	Day	Diet ¹				SEM	P-value	
		0% CT	1.2% CT	2.4% CT	3.5% CT		Linear	Quadratic
Initial BW, kg	0	347	350	349	339	4.2	0.21	0.13
Final BW, kg	52	436	437	432	421	6.4	0.077	0.35
DMI, kg/d	42 to 52	9.83	10.28	10.39	9.28	0.43	0.43	0.076
DMI, % BW	42 to 52	2.29	2.39	2.44	2.21	0.08	0.64	0.052
ADG_{Reg} ² , kg/d	0 to 52	1.79	1.70	1.67	1.64	0.10	0.27	0.76
ADG, kg/d	42 to 52	1.82	1.81	1.74	1.28	0.24	0.12	0.34
G:F, g/kg	42 to 52	187	175	166	132	22.2	0.09	0.62
Plasma urea N, mg N/L	52	158	141	96.7	77.6	6.78	<0.001	0.86

¹CT = condensed tannin extract from *Acacia mearnsii*. Cattle assigned to the 1.2, 2.4, and 3.5% CT diets (DM basis) were fed 0.6% CT during a 21-d transition from a backgrounding to a finishing diet and then the CT was increased in 0.6% increments at 4 to 7 d intervals until all cattle were fed the CT concentration of their assigned treatments (at day 42). Cattle were fed their treatment diets for an additional 10 d (to 52 d; 9 steers per dietary treatment).

²Average daily gain was determined from the coefficient of the linear regression relationship between 4% shrunk BW as the dependent variable and time as the independent variable.

Figure 1. Dry matter intake of beef steers individually fed 0, 1.2, 2.4, and 3.5% (DM basis) condensed tannin extract (CT) from *Acacia mearnsii*. Steers assigned to the 1.2, 2.4, and 3.5% CT treatments were fed 0.6% CT during a 21-d transition from a backgrounding to a finishing diet containing 20% DG, and then, the CT was increased in 0.6% increments at 4- to 7-d intervals until all steers were fed the CT concentration of their assigned treatments (at day 42). Steers were fed their treatment diets for an additional 10 d (to day 52). The arrows and corresponding values denote the day and level that the CT of the diet was increased. Each point represents the mean of 9 steers (SEM = 0.39 kg/d; diet $\times$ time $P = 0.005$).

trend toward a quadratic response ($P = 0.08$), with no effect ($P \geq 0.35$) of CT on DMI at 1.2% and 2.4% of the diet, but tendency toward a decrease ($P = 0.07$) in DMI for cattle fed 3.5% CT compared with 2.4% CT (Table 2). Likewise, there was tendency toward a quadratic response ($P = 0.052$) when DMI was expressed as a percentage of BW, where there was no effect of CT on DMI at 1.2% and 2.4% of the diet ($P \geq 0.19$), but a tendency toward a decrease ($P = 0.054$) in DMI as a percentage of BW for cattle fed 3.5% CT compared with 2.4% CT.

The ADG determined for the duration of the experiment did not differ ($P \geq 0.27$) among cattle fed the dietary treatments and averaged 1.70 ± 0.10 kg/d. The ADG determined for the last 10 d of the experiment was also not affected by the increasing CT concentration, although ADG was numerically less for steers fed 3.5% CT ($P = 0.12$, linear). There was a trend toward a linear decrease ($P = 0.09$) in G:F with increasing CT concentration. Increasing CT concentration of the diet had a strong linear effect ($P < 0.001$) on reducing PUN concentration.

Based on the results, a dietary concentration of 2.5% CT (DM basis) was selected for inclusion in a high-protein diet containing 40% DG and CT of Exp. 2. This was similar to the highest dietary concentration of CT extract (2.4%) with no adverse effects on DMI.

Experiment 2. Growth Performance and Ammonia Emissions

The diet $\times$ period interaction was not significant for DMI ($P = 0.13$) and ADG ($P = 0.29$), and although there was tendency ($P = 0.07$) toward significance for G:F, there were no differences between the 40DG and 40DGCT for 3 of the 4 periods; therefore, means and SEM are presented for the main effect of diet only (Table 3). The BW of cattle after the 14-d adaptation period averaged 457 ± 3.8 kg. There was no effect of the dietary treatments on final BW (621 ± 7.1 kg, $P = 0.82$) and DMI (11.9 ± 0.25 kg/d, $P = 0.15$), although DMI expressed as a percentage of BW was greater ($P \leq 0.05$) for steers fed the 3 dietary treatments containing DG (20DG, 40DG, and 40DGCT) than for steers fed 0DG. There was no effect of DG and CT on ADG, which averaged 1.98 ± 0.07 kg/d ($P = 0.56$), and G:F, which averaged 165 ± 5.4 g/kg ($P = 0.25$). There were also no effects ($P \geq 0.16$) of the dietary treatments on carcass traits. Dressing percentage averaged $63.2 \pm 0.29\%$, grade fat (back fat) 16.0 ± 0.82 mm, and lean yield $51.8 \pm 0.81\%$. Quality grades of the carcasses were 1% Prime, 65% AAA, and 34% AA.

The PUN averaged across time points was greatest for 40DG, intermediate for 40DGCT and 20DG, and least for the feedlot steers fed 0DG ($P < 0.001$, Table 3), although the interaction between diet and time was significant ($P < 0.001$). As expected, there was no difference ($P \geq 0.27$) in PUN of cattle on day 0 prior receiving their dietary treatments, but by day 14 and every 3 wk subsequently, PUN was less ($P \leq 0.05$) in cattle fed 40DGCT compared with 40DG and either equal to (at days 14, 36, and 96, $P \geq 0.49$) or less than (at days 55 and 76, $P \leq 0.05$) PUN of the cattle fed 20DG (Fig. 2).

Ruminal fermentation characteristics were measured in all cattle in the isolated pens 2 to 3 h after feeding (Table 4). Increasing the proportion of DG to 20% of diet DM, reduced ($P < 0.03$) ruminal pH compared with 0DG, but a further increase to 40% DG had no effect on ruminal pH ($P = 0.64$). Ruminal pH was reduced ($P = 0.01$) in cattle fed 40DGCT compared with 40DG. There was no effect ($P \geq 0.11$) of the dietary treatments on total VFA concentration, the molar proportions of acetate, propionate, and the acetate to propionate ratio. The 40DGCT treatment yielded greater ($P < 0.001$) molar proportions of butyrate compared with 0DG, but the proportions were similar between 40DGCT and 40DG. Branched chain acids were less ($P = 0.03$) in cattle fed 40DGCT

Table 3. Performance of beef feedlot cattle fed high-protein finishing diets containing corn distillers grains and condensed tannins

Item	Diet ¹				SEM	P-value
	0DG	20DG	40DG	40DGCT		
Initial BW, kg	459	456	457	456	3.8	0.95
Final BW, kg	624	625	621	616	7.1	0.82
DMI, kg/d	11.4	12.1	12.1	12.1	0.25	0.15
DMI, % BW	2.09 ^b	2.21 ^a	2.23 ^a	2.24 ^a	0.04	0.042
ADG _{Reg} ² , kg/d	1.99	2.06	1.96	1.91	0.07	0.56
G:F, g/kg	175	167	163	159	5.4	0.25
Carcass traits						
Hot carcass weight, kg	382	381	382	378	3.3	0.86
Dressing percentage, %	63.1	63.1	63.2	63.1	0.29	0.99
Longissimus muscle area, cm ²	83.4	83.4	84.1	83.0	1.29	0.95
Grade fat ³ , mm	14.4	16.0	17.3	16.3	0.82	0.16
Average fat ⁴ , mm	16.4	18.2	19.7	18.4	0.99	0.21
Marbling score ⁵	45.2	36.7	47.5	50.8	5.89	0.42
Lean yield ⁶ , %	53.0	51.7	50.8	51.6	0.81	0.35
Quality grade, %						
Prime	0	0	0	3.7	—	—
AAA	55.6	70.4	80.6	53.2	—	0.59
AA	44.4	29.6	19.4	43.1	—	0.34
Plasma urea N ⁷ , mg N/L	113 ^c	153 ^b	170 ^a	146 ^b	2.9	<0.001

^{a-c}Within a row, means without a common superscript differ ($P \leq 0.05$, $n = 16$ pens for BW, DMI ADG_{Reg}, G:F and plasma urea N, and $n = 12$ pens for carcass traits).

¹0DG = no corn dried distillers grains and solubles (DG), 20DG = 20% of diet DM as DG, 40DG = 40% of diet DM as DG, 40DGCT = 40% of diet DM as DG and 2.5% of diet DM as condensed tannin extract of *Acacia mearnsii*.

²Average daily gain was determined from the coefficient of the linear regression relationship between 4% shrunk BW as the dependent variable and time as the independent variable.

³Backfat thickness measured between the 12th and 13th rib.

⁴The average of 3 measures of fat thickness of the longissimus muscle area.

⁵Marbling score of 60.0 to 69.9 = modest, 50.0 to 59.9 = small, 40.0 to 49.9 = slight, and 30.0 to 39.9 = traces.

⁶Lean meat yield, % = $57.96 - (0.027 \times \text{hot carcass weight, kg}) + (0.202 \times \text{longissimus muscle area, cm}^2) - (0.703 \times \text{average fat, mm})$ (Bergen et al., 1996).

⁷Diet $\times$ time interaction, $P < 0.001$ (Fig. 2).

compared with 40DG and in cattle fed the 20DG compared with the 0DG. Feeding CT with 40% DG tended to also reduce ruminal NH₃-N concentration (40DGCT vs. 40DG, $P = 0.09$).

Micrometeorological conditions observed during each of the 4-d measurement periods for NH₃-N emissions from cattle in the 2 isolated pens are reported in Table 5. The average temperature for each period increased from 7.3 to 15.7 °C from late April to early July and ranged from a minimum of -1.9 to a maximum of 25.6 °C. Wind speed for each period averaged from 2.3 to 3.5 m/s. Wind speed was <10 m/s except for 1 d during the period of 19 to 23 May where 24% of the 30-min measurements were >10 m/s with a maximum wind speed of 13.9 m/s. During the second measurement period, rainfall (1.6 mm) on 20 May wet the inner surface of the passive flux samplers; therefore, data for the 24-h collection beginning on this day were not

used and data for an additional 24 h were collected. Cumulative rainfall was ≤ 0.2 mm for the 4 $\times$ 24 h for the first 3 periods and was 3.4 mm during the fourth measurement period from 30 June to 3 July.

Ammonia-N emissions tended ($P = 0.11$) to increase from 26.3 to 51.3 ± 11.2 g N/(steer·d) for beef feedlot cattle fed 0DG and 20DG, respectively, although not when expressed as % N intake ($P = 0.19$, Table 6). The relatively high variation for NH₃-N emissions observed for the steers fed 0DG and 20DG from 30 April to 4 May was due in part to suppression of emissions by the low air temperature (<5 °C) for the first 2 d of measurement (Fig. 3). Ammonia-N emissions were increased ($P = 0.003$) by 61% from 70.8 to 113.7 g N/(steer·d) for the cattle fed 0DG and 40DG, respectively. When expressed as a % N intake, NH₃-N emissions tended ($P < 0.11$) to increase from 30.3% to 33.6% for cattle fed 0DG compared with 40DG. Emissions

Figure 2. Plasma urea N in feedlot cattle fed 0, 20, and 40% corn dried distillers grains and solubles (DG), and 40% DG with 2.5% condensed tannin extract (CT) from *Acacia mearnsii*. Each point is the mean of 4 pens of cattle (SEM 5.9 mg N/L; diet $\times$ time $P < 0.001$). At days 14, 36, 55, 76, and 97, PUN was lower ($P \leq 0.05$) in cattle fed 40DGCT compared with 40DG and either equal to (at days 14, 36, and 96, $P \geq 0.49$) or less than (at days 55 and 76; $P \leq 0.05$) PUN of the cattle fed 20DG.

tended [30.4 vs. 44.1 g N/(steer·d), $P = 0.13$] to be 45% greater for cattle fed 40DGCT compared with 0DG, which was lower than the 61% increase in emissions for cattle fed 0DG compared with 40DG. There was no difference between cattle fed 0DG and 40DGCT when NH_3 -N emissions were expressed as % N intake. Feeding CT with the 40% DG tended to decrease the amount [72.7 vs. 95.1 g N/(steer·d); $P = 0.09$] and proportion (20.5 vs. 26.5 % N intake; $P = 0.11$) of NH_3 -N emissions from the cattle by about 23% compared with 40DG.

DISCUSSION

Feeding tannins may have a role in improving environmental sustainability of ruminant production systems through reducing enteric methane emissions (Carulla et al., 2005; Beauchemin et al., 2007; Grainger et al., 2009), nitrate leaching, and nitrous oxide emissions in grazing systems (Griffiths et al., 2013), and, as in the current study, ammonia emissions from confined animal feeding operations

Table 4. Ruminal fermentation characteristics of beef feedlot cattle fed high-protein finishing diets containing distillers grains and condensed tannins^{1,2}

Item	Period 1		Period 2		Period 3		Period 4	
	0DG	20DG	40DG	40DGCT	0DG	40DG	0DG	40DGCT
pH	6.60	6.20	6.70	6.14	6.42	6.51	6.64	6.31
SEM	0.12		0.15		0.12		0.14	
P-value	0.033		0.011		0.64		0.101	
Total VFA, mM	111	109	95.0	113	106	97.0	108	106
SEM	7.1		7.6		6.7		6.1	
P-value	0.83		0.11		0.35		0.83	
Individual VFA, mol/100 mol								
Acetate	44.0	44.7	47.3	44.9	48.3	47.5	47.7	46.0
SEM	0.65		1.19		0.86		1.21	
P-value	0.45		0.17		0.51		0.32	
Propionate	41.1	42.0	36.0	38.0	38.1	38.6	40.0	38.6
SEM	1.60		2.0		1.44		1.80	
P-value	0.72		0.49		0.78		0.59	
Butyrate	9.56	8.55	11.2	12.6	7.97	8.74	7.56	11.0
SEM	1.07		1.01		0.46		0.62	
P-value	0.51		0.31		0.27		<0.001	
Branched chain acids ³	2.53	1.95	2.65	1.92	3.04	2.24	2.47	2.00
SEM	0.18		0.21		0.43		0.26	
P-value	0.033		0.026		0.20		0.20	
Acetate:propionate ratio	1.12	1.07	1.37	1.23	1.30	1.25	1.20	1.24
SEM	0.08		0.12		0.08		0.10	
P-value	0.68		0.41		0.63		0.76	
Ammonia N, mg N/L	23.6	27.0	44.0	25.5	38.0	35.7	33.0	26.9
SEM	5.70		7.59		7.49		3.72	
P-value	0.67		0.095		0.82		0.24	

¹0DG = no corn dried distillers grains and solubles (DG), 20DG = 20% of diet DM as DG, 40DG = 40% of diet DM as DG, 40DGCT = 40% of diet DM as DG and 2.5% of diet DM as condensed tannin extract of *Acacia mearnsii*.

²Ten steers per pen.

³Isobutyrate and isovalerate.

Table 5. Temperature, wind speed, and rainfall during measurement of ammonia emissions from cattle fed high-protein finishing diets containing corn distillers grains and condensed tannins

Date ¹	Air temperature, °C			Wind speed, m/s			Cumulative rainfall, mm
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum	
30 April to 4 May	7.3 ± 0.54	−1.9	18.6	3.4 ± 0.40	0.5	7.5	0
19 to 24 May	11.6 ± 0.28	−0.3	22.5	3.5 ± 0.44	0.2	13.9	0.2
9 to 13 June	14.0 ± 0.27	2.3	25.6	2.3 ± 0.14	0.2	6.8	0.2
30 June to 4 July	15.7 ± 0.06	8.7	23.1	2.6 ± 0.11	0.2	8.7	3.4

¹Measured for 4 consecutive 24-h days, except from 19 to 24 May where data for 20 May was not included due to rain wetting the inner surface of the passive flux samplers.

Table 6. Ammonia-N emissions from beef feedlot cattle fed high-protein finishing diets containing corn distillers grains and condensed tannins

Date ¹	Diet ²	N intake, g/d	Ammonia N, g N/(steer·d)	SED	P-value	Ammonia N, % N intake	SED	P-value
30 April to 4 May	0DG	203	26.3	11.2	0.11	13.0	3.82	0.19
	20DG	264	51.3			19.4		
19 to 24 May	40DG	359	95.1	9.30	0.09	26.5	2.64	0.11
	40DGCT	354	72.7			20.5		
9 to 13 June	0DG	234	70.8	4.57	0.003	30.3	1.47	0.11
	40DG	338	113.7			33.6		
30 June to 4 July	0DG	214	30.4	5.54	0.13	14.2	2.12	0.42
	40DGCT	360	44.1			12.3		

¹Measured for 4 consecutive 24 h, except from 19 to 24 May where data for 20 May was not included due to rain wetting the inner surface of the passive flux samplers.

²0DG = no corn dried distillers grains and solubles (DG), 20DG = 20% of diet DM as DG, 40DG = 40% of diet DM as DG, 40DGCT = 40% of diet DM as DG and 2.5% of diet DM as condensed tannin extract of *Acacia mearnsii*.

(Misselbrook et al., 2005; Powell et al., 2011). Feeding a CT extract from *A. mearnsii* to beef cattle fed high-protein finishing diets containing 40% corn DG reduced NH₃-N emissions from the feedlot pen and lowered PUN suggesting a reduction in dietary CP digestibility and a shift in excess N excretion from labile urea N in urine to CT–protein complexes in manure. The CT extract at 2.5% (1.33% CT) of diet DM had no negative effect on feed intake, growth rate, feed efficiency (G:F), and carcass traits of finishing beef feedlot cattle. For CT to be considered as a nutritional strategy to mitigate NH₃-N emissions and improve whole farm nutrient utilization there can be no detrimental effects on the major economic performance indicators and carcass quality.

Animal Performance

In general, forages containing moderate concentrations of CT (2 to 4.5% DM) have shown no adverse effects on animal production, but at higher concentrations (>5.5% DM), feed intake, nutrient digestibilities, and performance are reduced (Min et al., 2003). The results of this study suggest that the upper limit for the CT extract of *A. mearnsii* is 2.5% (1.33% CT) in a high-protein finishing diet

for beef cattle. The CT extract from *A. mearnsii* did not affect DMI of beef cattle when introduced in stepwise increments up to 2.4% and 2.5% (1.27 and 1.33% CT, respectively) of high-protein finishing diets consisting of barley grain with 20 and 40% corn DG, respectively, but DMI was reduced when the concentration was increased to 3.5% (1.9% CT) of DM. The CT extract at 2.5% DM had no negative effects on ADG, G:F, and carcass traits of feedlot cattle. This is consistent with a companion metabolism experiment where 2.5% of the CT extract was supplemented to a similar TMR containing 40% corn DG and 20% CP with no negative effects on DM and nutrient intake of beef heifers (Koenig and Beauchemin, 2018). A higher dietary concentration of 4.1% CT extract (2.5% CT) of *A. mearnsii* was fed to growing sheep fed a forage-based diet and a small but significant increase in DMI was observed (Carulla et al., 2005), although generally dietary concentrations of the CT extract at or above 2.0% to 2.5% (1 to 1.5% CT) have had various negative effects on feed intake and performance depending on the CP content of the diet and protein requirements of the animal. When the CT extract of *A. mearnsii* was orally drenched twice daily to grazing lactating dairy cattle at an estimated concentration of 1.43% and 2.42% (0.86 and 1.46% CT) of

Figure 3. Daily micrometeorological conditions and ammonia-N emissions from beef feedlot cattle fed high-protein barley-based finishing diets with (a) no dried distillers grains and solubles (0DG) vs. 20% DG (20DG), (b) 40% DG (40DG) vs. 40DG with 2.5% condensed tannin extract (40DGCT), (c) 0DG vs. 40DG, and (d) 0DG vs. 40DGCT.

the diet containing 22% CP, feed intake was reduced by 5% and 8.5% and milk production by 3.6% and 9.7%, respectively (Grainger et al., 2009). In the same study, when the CT extract of *A. mearnsii* was fed at 1.79% and 3.17% (1.1 and 1.9% CT) of the diet with 16% CP to a subset of the lactating dairy cattle, feed intake was reduced by 13.2% and 26.4%

and milk production by 22.4% and 29.8%, respectively. The detrimental effects of the CT in dairy cattle were more pronounced at a lower dietary CP and when CP was below requirements. In a similar study, where the CT extract of *A. mearnsii* was drenched or provided in a grain-based pellet, there was no reduction in intake at 1.1% (0.6% CT) and a

5% reduction at 2.34% (1.4% CT), but no effect on milk production of dairy cows fed the lower level of CT supplementation and adequate CP (Griffiths et al., 2013). Krueger et al. (2010) fed the CT extract (*A. mearnsii*) at 1.49% of a corn grain finishing diet with 13% CP and found no effect of the CT supplementation on DMI, ADG, G:F, and carcass traits, except for hot carcass weight which was 3.7% lower than steers fed no CT. There was, however, also no effect of the CT extract on ruminal NH_3 , suggesting that the dietary concentration was too low to affect N digestibility. It was noted that cattle were initially supplemented with tannin extracts at 2.0% DM, but feed intake was reduced for several days and, therefore, the dietary concentration was reduced for the study. In the current study, the introduction of the CT extract into the diet in stepwise increments may have allowed for adaptation and acceptance of higher dietary concentrations.

The primary mechanisms of action by which CT reduce NH_3 emissions is through reduced protein degradation within the gastrointestinal tract, increased output of CT–protein complexes in feces, and hence a reduction in the excretion of urea N in urine. Condensed tannins combine with dietary protein to form stable complexes resistant to proteolysis in the rumen within a pH range of 5.5 to 6.5 (Jones and Mangan, 1977). Condensed tannins can also bind microbial cells and enzymes and reduce ruminal fermentation (McSweeney et al., 2001; Smith et al., 2005). Dissociation of the dietary protein from the CT can occur at the lower pH the abomasum (<3.0) with increased passage, digestion, and absorption of AA in the small intestine. The increase in dietary protein availability at the small intestine probably contributes in part to improvements in weight gain, milk production, and wool growth (Waghorn, 2008). In the current study, ruminal NH_3 -N, PUN, and NH_3 -N emissions were lower for cattle fed the CT extract (40DGCT vs. 40DG) suggesting a reduction in protein degradation in the rumen and small intestine. This may occur due to incomplete dissociation of the dietary protein from the CT within the abomasum, reformation of the CT-dietary protein complex at the pH in the small intestine, and complexation of the CT to host digestive enzymes and the intestinal mucosa preventing proteolysis and AA absorption (Waghorn, 2008).

Supplementation of the CT extract to the diet with 40% DG (40DGCT vs. 40DG) reduced ruminal NH_3 -N concentration (25.5 vs. 44 mg N/L) indicating reduced ruminal protein degradation. There was, however, no effect on ruminal total

VFA concentration suggesting that microbial fermentation and OM digestibility in the rumen was not adversely affected. Plasma urea N concentration was also reduced (146 vs. 170 mg N/L) with supplementation of the CT extract (40DGCT vs. 40DG). Similar effects were reported for heifers fed 40% DG with and without the CT extract in a companion metabolism experiment (Koenig and Beauchemin, 2018) for ruminal NH_3 -N (70 vs. 106 mg N/L) and PUN (172 vs. 202 mg N/L) and with confirmation of reduced urinary urea-N excretion and an increase in output of CT–protein complexes in feces (i.e., NDIN and ADIN; Powell et al., 2009). Ruminal NH_3 -N in the feedlot steers could be considered marginal to meet microbial N requirements and support maximal growth of ruminal microorganisms (Satter and Slyter, 1974). However, ruminal fluid was collected 2 to 3 h after feeding, which coincides with the lowest ruminal NH_3 -N concentration relative to the time of once a day feed allocation (Koenig and Beauchemin, 2013). In addition, ruminal fluid was collected by an oral ruminal probe, which can be more difficult to place in the ventral rumen and prone to salivary contamination (Geishauser, 1993; Duffield et al., 2004). Ruminal pH ranged from 6.14 to 6.70 and was approximately 0.8 pH units greater than that observed at 2 to 3 h after feeding using indwelling ruminal pH probes in the beef heifers of the companion study (Koenig and Beauchemin, 2018) indicating minimal salivary contamination of the sample. Supplementing the CT extract reduced PUN in cattle (40DGCT vs. 40DG) at each of the 3-wk time points from days 14 to 83 of the feedlot experiment. The efficacy of the CT extract to reduce protein digestion was sustained over the long-term suggesting that there was limited microbial (McSweeney et al., 2001; Smith et al., 2005) and physiological adaptation (Makkar and Becker, 1998; Salem et al., 2013). The combined results of the present study and the companion metabolism study indicate reduced total tract protein digestion and a shift in the route of excess N excretion from urea N in urine to CT–protein complexes in feces of the feedlot cattle fed the CT extract with 40% DG compared with the 40% DG without the extract.

Ammonia Emissions

Recommendations for feeding DG typically range from 15% to 20% of the finishing diet DM but inclusion can be as high as 50% (Vasconcelos and Galyean, 2007; Klopfenstein et al., 2008). Protein and P (K and other minerals) in DG are

3 times the concentration of the parent grain (Klopfenstein et al., 2008; Liu, 2011), and as a result, protein and P requirements of cattle are now routinely exceeded and will, therefore, affect subsequent management of nutrients within the whole farm system. The CP content of finishing diets ranges from 12.0% to 14.5% when balanced for RDP and RUP. The CP content of the barley-based finishing diets was 13% and increased to 16% and 20% when corn DG was substituted for barley grain at 20 and 40% DM, respectively, and is in agreement with other studies (Walter et al., 2010; Hünerberg et al., 2013). Excess CP whether in the form of rumen degradable protein or rumen undegradable protein is degraded within the gastrointestinal tract, and the end products are absorbed into the blood, metabolized by the liver, and largely excreted as urea in urine, the major nitrogenous form in urine (Bristow et al., 1992). Urea N is rapidly hydrolyzed (<24 h) to CO_2 and NH_4^+ by bacterial urease excreted in the feces of cattle (Muck, 1982). The NH_4^+ formed dissociates to aqueous NH_3 depending on the NH_4^+ concentration, ambient temperature, and pH. Transfer of NH_3 from the aqueous to the gaseous phase is then dependent on temperature and wind speed (Sommer et al., 1991). Fecal N is composed largely of bacterial N, endogenous N, and undigested feed N (NRC, 1985) and is less prone to NH_3 volatilization (Mulvaney et al., 2008). For feedlot cattle, N loss from the pen is predominantly from manure in the form of gaseous NH_3 -N (Hutchinson et al., 1982; Todd et al., 2005; McGinn et al., 2007).

The integrated horizontal flux technique with passive NH_3 samplers was designed for the quantitative measurement of NH_3 emissions from small agronomic plots and manure storage facilities and has been adapted for research scale feedlot pens (McGinn and Sommer, 2007; Koenig et al., 2013). Bypass of NH_3 -N between the 2 tubes (i.e., from the inward facing tube to the outward facing tube or vice versa) with a 7-cm length of oxalic acid coating is negligible provided the NH_4^+ -N content of the tube is <50 μg and the wind speed <10 m/s (Sommer et al., 1996). All of the 2,048 (9-cm) tubes contained <50 μg N indicating that the oxalic acid coating did not become saturated with NH_4^+ -N for the 24 h of collection. Mean wind speed during the measurement of NH_3 -N emissions ranged from 2.6 to 3.5 m/s. Wind speed was <10 m/s except for 1 d during the period of 19 to 23 May where 24% of the 30-min measurements were >10 m/s. Bypass can be assessed by plotting the amount of NH_3 -N in the tubes facing away from the source (background

tubes) vs. the amount of NH_3 -N in the tubes facing toward the source (Sommer et al., 1996; Warren et al., 2006; Cabrera et al., 2011). When bypass is observed, NH_3 -N emissions are calculated by adding the NH_3 -N in the background and exposed tubes instead of subtracting the NH_3 -N in background from the exposed tubes. Linear regression of the absorbed NH_3 -N in the background tubes vs. the inward facing tubes on the upwind side of each of the 2 pens was not significant (data not shown), indicating that there was no bypass of NH_3 -N from the inward facing tubes to the background tubes when wind speeds were >10 m/s. Therefore, there was quantitative capture of NH_3 -N in the passive flux samplers.

Ammonia emissions from feedlot cattle increased with increasing concentrations of CP in the finishing diets containing 20 (from 26.3 to 51.3 g N/d) and 40% (from 70.8 to 113.7 g N/d) DG compared with a barley-based diet with no DG. When NH_3 -N emissions were expressed as a percentage of N intake, no differences were detected between the diets with no DG and 20% DG (13.0% vs. 19% of N intake), but at 40% DG, there was an 11% increase in emissions (30.3 vs. 33.6% N intake). Supplementation of the CT extract to the 40% DG diet reduced NH_3 -N emissions by approximately 23% from 95.1 to 72.7 g N/d and 26.5% to 20.5% of N intake.

In addition to feeding and management practices, environmental conditions also affect NH_3 -N formation and emissions from the feedlot pen (Waldrip et al., 2015). Mean daily air temperature during the first 4-d period ranged from 3.6 °C on 30 April to 12.4 °C on 3 May. During this period, NH_3 -N emissions were lower for the first 3 d when the temperature was ≤ 8.5 °C and may have been inhibited by the low temperature (Pereira et al., 2012). The NH_3 -N emissions were also lower for the last period from 30 June to 3 July. The mean air temperature was consistent from day to day and averaged 15.7 °C, and the minimum was >8.5 °C. There was 3.4 mm of rain over the first 2 d, which may have suppressed emissions for the 2 d of rainfall and the subsequent 2 d. Rain can inhibit NH_3 -N emissions but is usually followed by a flush of emissions upon drying (McGinn et al., 2007).

In this study, DG at 40% of DM was at the upper end of the recommended inclusion range, and when combined with barley grain that has a higher CP concentration than corn grain, the CP concentration of the total diet reached 20%. The inclusion of 2.5% CT extract of *A. mearnsii* in the diet of cattle fed 40% DG reduced NH_3 -N emissions by 23%

compared with cattle fed 40% DG, with no negative effect on growth performance. Ammonia emissions from livestock production cannot be eliminated, but they can be minimized and managed to reduce the effects on human health and the environment. Development of plant secondary metabolites as natural feed additives to influence N metabolism and excretion to capture a greater proportion of feed N in meat and manure will enable beef cattle producers to take advantage of the economics of existing feeds and new by-product feeds in environmentally sustainable production systems.

LITERATURE CITED

- AOAC. 2016. Official methods of analysis. 20th ed. Assoc. Off. Anal. Chem. Int., Gaithersburg, MD.
- Beauchemin, K. A., S. M. McGinn, T. F. Martinez, and T. A. McAllister. 2007. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *J. Anim. Sci.* 85:1990–1996. doi:10.2527/jas.2006-686
- Bergen, R. D., J. J. McKinnon, D. A. Christensen, and N. Kohle. 1996. Prediction of lean yield in yearling bulls using real-time ultrasound. *Can. J. Anim. Sci.* 76:305–311. doi:10.4141/cjas96-046
- Bristow, A. W., D. C. Whitehead, and J. E. Cockburn. 1992. Nitrogenous constituents in the urine of cattle, sheep and goats. *J. Sci. Food Agric.* 59:387–394. doi:10.1002/jsfa.2740590316
- Cabrera, M. L., N. Vaio, J. Rema, L. Braun, and D. E. Kissel. 2011. Comparison of two passive flux methods to measure ammonia volatilization. *Soil Sci. Soc. Am. J.* 75:949–956. doi:10.2136/sssaj2010.0309
- Canadian Council on Animal Care. 2009. CCAC guidelines on: The care and use of farm animals in research, teaching and testing. Canadian Council on Animal Care, Ottawa, ON. https://www.ccac.ca/Documents/Standards/Guidelines/Farm_Animals.pdf (Accessed 29 November 2017.)
- Canadian Food Inspection Agency. 2012. Livestock and Poultry Carcass Grading Regulations (SOR/95–216, s 2), Consolidation. Part III. <http://laws-lois.justice.gc.ca/eng/regulations/SOR-92-541/index.html> (Accessed 29 November 2017.)
- Carulla, J. E., M. Kreuzer, A. Machmüller, and H. D. Hess. 2005. Supplementation of *Acacia mearnsii* tannins decreases methanogenesis and urinary nitrogen in forage-fed sheep. *Aust. J. Agric. Res.* 56:961–970. doi:10.1071/AR05022
- Duffield, T., J. C. Plaizier, A. Fairfield, R. Bagg, G. Vessie, P. Dick, J. Wilson, J. Aramini, and B. McBride. 2004. Comparison of techniques for measurement of rumen pH in lactating dairy cows. *J. Dairy Sci.* 87:59–66. doi:10.3168/jds.S0022-0302(04)73142-2
- ECCC. 2016. 1990–2015 Air pollution emission inventory report. Environ. Clim. Change Canada, Gatineau, QC.
- Geishauser, T. 1993. An instrument for collection and transfer of ruminal fluid and for administration of water soluble drugs in adult cattle. *Bovine Pract.* 27:38–42.
- Grainger, C., T. Clarke, M. J. Auldist, K. A. Beauchemin, S. M. McGinn, G. C. Waghorn, and R. J. Eckard. 2009. Potential use of *Acacia mearnsii* condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. *Can. J. Anim. Sci.* 89:241–251. doi:10.4141/CJAS08110
- Griffiths, W. M., C. E. Clark, D. A. Clark, and G. C. Waghorn. 2013. Supplementing lactating dairy cows fed high-quality pasture with black wattle (*Acacia mearnsii*) tannin. *Animal* 7:1789–1795. doi:10.1017/S1757131113001420
- Hagerman, A. E. 2002. Tannin handbook. Miami University, Oxford, OH.
- Hagerman, A. E., and L. G. Butler. 1981. The specificity of proanthocyanidin-protein interactions. *J. Biol. Chem.* 256:4494–4497.
- Halvorson, J. J., S. L. Kronberg, and A. E. Hagerman. 2017. Effects of dietary tannins on total and extractable nutrients from manure. *J. Anim. Sci.* 95:3654–3665. doi:10.2527/jas.2016.1129
- Hristov, A. N., M. Hanigan, A. Cole, R. Todd, T. A. McAllister, P. M. Ndegwa, and A. Rotz. 2011. Review: Ammonia emissions from dairy farms and beef feedlots. *Can. J. Anim. Sci.* 91:1–35. doi:10.4141/CJAS10034
- Hünerberg, M., S. M. McGinn, K. A. Beauchemin, E. K. Okine, O. M. Harstad, and T. A. McAllister. 2013. Effect of dried distillers' grains with solubles on enteric methane emissions and nitrogen excretion from finishing beef cattle. *Can. J. Anim. Sci.* 93:373–385. doi:10.4141/cjas2012-151
- Hutchinson, G. L., A. R. Mosier, and C. E. Andre. 1982. Ammonia and amine emissions from a large cattle feedlot. *J. Environ. Qual.* 11:288–293. doi:10.2134/jeq1982.00472425001100020028x
- Jones, W. T., and J. L. Mangan. 1977. Complexes of the condensed tannins of sainfoin (*Onobrychis viciifolia* scop.) with fraction 1 leaf protein and with submaxillary mucoprotein, and their reversal by polyethylene glycol and pH. *J. Sci. Food Agric.* 28:126–136. doi:10.1002/jsfa.2740280204
- Kempers, A. J., and A. Zweers. 1986. Ammonium determination in soil extracts by the salicylate method. *Commun. Soil Sci. Plant Anal.* 17:715–723. doi:10.1080/00103628609367745
- Klopfenstein, T. J., G. E. Erickson, and V. R. Bremer. 2008. Board-Invited Review: Use of distillers by-products in the beef cattle feeding industry. *J. Anim. Sci.* 86:1223–1231. doi:10.2527/jas.2007-0550
- Koenig, K. M., and K. A. Beauchemin. 2013. Nitrogen metabolism and route of excretion in beef feedlot cattle fed barley-based backgrounding diets varying in protein concentration and rumen degradability. *J. Anim. Sci.* 91:2295–2309. doi:10.2527/jas.2012-5652
- Koenig, K. M., and K. A. Beauchemin. 2018. Effect of feeding condensed tannins in high protein finishing diets containing corn distillers grains on ruminal fermentation, nutrient digestibility, and route of nitrogen excretion in beef cattle. *J. Anim. Sci.* In press. doi: 10.1093/jas/sky273.
- Koenig, K. M., S. M. McGinn, and K. A. Beauchemin. 2013. Ammonia emissions and performance of backgrounding and finishing beef feedlot cattle fed barley-based diets varying in dietary crude protein concentration and rumen degradability. *J. Anim. Sci.* 91:2278–2294. doi:10.2527/jas.2012-5651
- Kononoff, P. J., A. J. Heinrichs, and D. R. Buckmaster. 2003. Modification of the Penn State forage and total mixed ration particle separator and the effects of moisture content on its measurements. *J. Dairy Sci.* 86:1858–1863. doi:10.3168/jds.S0022-0302(03)73773-4

- Krueger, W. K., H. Gutierrez-Bañuelos, G. E. Carstens, B. R. Min, W. E. Pinchak, R. R. Gomez, R. C. Anderson, N. A. Krueger, and T. D. A. Forbes. 2010. Effects of dietary tannin source on performance, feed efficiency, ruminal fermentation, and carcass and non-carcass traits in steers fed a high-grain diet. *Anim. Feed Sci. Technol.* 159:1–9. doi:10.1016/j.anifeedsci.2010.05.003
- Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simple method for the analysis of particle sizes of forage and total mixed rations. *J. Dairy Sci.* 79:922–928. doi:10.3168/jds.S0022-0302(96)76442-1
- Liu, K. S. 2011. Chemical composition of distillers grains: A review. *J. Agric. Food Chem.* 59:1508–1526. doi:10.1021/jf103512z
- Makkar, H. P. S., and K. Becker. 1998. Adaptation of cattle to tannins: Role of proline-rich proteins in oak-fed cattle. *Anim. Sci.* 67:277–281. doi:10.1017/S1357729800010031
- McGinn, S. M., T. K. Flesch, B. P. Crenna, K. A. Beauchemin, and T. Coates. 2007. Quantifying ammonia emissions from a cattle feedlot using a dispersion model. *J. Environ. Qual.* 36:1585–1590. doi:10.2134/jeq2007.0167
- McGinn, S. M., and S. G. Sommer. 2007. Ammonia emissions from land-applied beef cattle manure. *Can. J. Soil Sci.* 87:345–352. doi:10.4141/S06-053
- McSweeney, C. S., B. Palmer, D. M. McNeill, and D. O. Krause. 2001. Microbial interactions with tannins: Nutritional consequences for ruminants. *Anim. Feed Sci. Technol.* 91:83–93. doi:10.1016/S0377-8401(01)00232-2
- Min, B. R., T. N. Barry, G. T. Attwood, and W. C. McNabb. 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: A review. *Anim. Feed Sci. Technol.* 106:3–19. doi:10.1016/S0377-8401(03)00041-5
- Misselbrook, T. H., J. M. Powell, G. A. Broderick, and J. H. Grabber. 2005. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence on ammonia emissions. *J. Dairy Sci.* 88:1765–1777. doi:10.3168/jds.S0022-0302(05)72851-4
- Muck, R. E. 1982. Urease activity in bovine feces. *J. Dairy Sci.* 65:2157–2163. doi:10.3168/jds.S0022-0302(82)82475-2
- Mueller-Harvey, I. 2006. Unravelling the conundrum of tannins in animal nutrition and health. *J. Sci. Food Agric.* 86:2010–2037. doi:10.1002/jsfa.2577
- Mulvaney, M. J., K. A. Cummins, C. W. Wood, B. H. Wood, and P. J. Tyler. 2008. Ammonia emissions from field-simulated cattle defecation and urination. *J. Environ. Qual.* 37:2022–2027. doi:10.2134/jeq2008.0016
- NRC. 1985. Ruminant nitrogen usage. Natl. Acad. Press, Washington, DC.
- NRC. 2000. Nutrient requirements of beef cattle. Update. 7th rev. ed. Natl. Acad. Press, Washington, DC.
- Pereira, J., T. H. Misselbrook, D. R. Chadwick, J. Coutinho, and H. Trindade. 2012. Effects of temperature and dairy cattle excreta characteristics on potential ammonia and greenhouse gas emissions from housing: A laboratory study. *Biosyst. Eng.* 112:138–150. doi:10.1016/j.biosystemseng.2012.03.011
- Powell, J. M., M. J. Aguerre, and M. A. Wattiaux. 2011. Tannins extracts abate ammonia emissions from simulated dairy barn floors. *J. Environ. Qual.* 40:907–914. doi:10.2134/jeq2010.0492
- Powell, J. M., G. A. Broderick, J. H. Grabber, and U. C. Hymes-Fecht. 2009. Technical note: Effects of forage protein-binding polyphenols on chemistry of dairy excreta. *J. Dairy Sci.* 92:1765–1769. doi:10.3168/jds.2008-1738
- Renewable Fuels Association. 2017. Building partnerships | growing markets. 2017 Ethanol industry outlook. <http://www.ethanolrfa.org/wp-content/uploads/2017/02/Ethanol-Industry-Outlook-2017.pdf> (Accessed 29 November 2017.)
- Salem, A. Z. M., S. López, M. J. Ranilla, and J. S. González. 2013. Short- to medium-term effects of consumption of quebracho tannins on saliva production and composition in sheep and goats. *J. Anim. Sci.* 91:1341–1349. doi:10.2527/jas.2010-3811
- Satter, L. D., and L. L. Slyter. 1974. Effect of ammonia concentration of rumen microbial protein production in vitro. *Br. J. Nutr.* 32:199–208. doi:10.1079/BJN19740073
- Schjoerring, J. K., S. G. Sommer, and M. Ferm. 1992. A simple passive sampler for measuring ammonia emission in the field. *Water Air Soil Pollut.* 62:13–24. doi:10.1007/BF00478450
- Smith, A. H., E. Zoetendal, and R. I. Mackie. 2005. Bacterial mechanisms to overcome inhibitory effects of dietary tannins. *Microb. Ecol.* 50:197–205. doi:10.1007/s00248-004-0180-x
- Sommer, S. G., J. E. Olesen, and B. T. Christensen. 1991. Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. *J. Agric. Sci.* 117:91–100. doi:10.1017/S0021859600079016
- Sommer, S. G., E. Sibbesen, T. Nielsen, J. K. Schjørring, and J. E. Olesen. 1996. A passive flux sampler for measuring ammonia volatilization from manure storage facilities. *J. Environ. Qual.* 25:241–247. doi:10.2134/jeq1996.00472425002500020006x
- Tedeschi, L. O., C. A. Ramírez-Restrepo, and J. P. Muir. 2014. Developing a conceptual model of possible benefits of condensed tannins for ruminant production. *Animal* 8:1095–1105. doi:10.1017/S1751731114000974
- Todd, R. W., N. A. Cole, L. A. Harper, T. K. Flesch, and B. H. Beak. 2005. Ammonia and gaseous nitrogen emissions from a commercial beef cattle feedyard estimated using the flux-gradient method and N:P ratio analysis. In: P. J. Nowack, editor, *Proc. State Sci.: Anim. Manure Waste Manag.* Natl. Centre Manure Anim. Waste Manag., San Antonio, TX. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.490.4096&rep=rep1&type=pdf> (Accessed 17 December 2017.)
- USEPA. 2014. National Emissions Inventory (NEI). US Environ. Prot. Agenc., Washington, DC. <https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data> (Accessed 29 November 2017.)
- Vasconcelos, J. T., and M. L. Galyean. 2007. Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University survey. *J. Anim. Sci.* 85:2772–2781. doi:10.2527/jas.2007-0261
- Waghorn, G. 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production – Progress and challenges. *Anim. Feed Sci. Technol.* 147:116–139. doi:10.1016/j.anifeedsci.2007.09.013
- Waghorn, G. C., I. D. Shelton, and W. C. McNabb. 1994. Effect of condensed tannins in *Lotus pedunculatus* on its nutritive value for sheep. I. Non-nitrogenous aspects. *J. Agric. Sci. (Camb.)* 123:99–107. doi:10.1017/S0021859600067824
- Waldrup, H. M., N. A. Cole, and R. W. Todd. 2015. Nitrogen

- sustainability and beef cattle feedyards: II. Ammonia emissions. *Prof. Anim. Sci.* 31:395–411. doi:10.15232/pas.2015-01395
- Walter, L. J., J. L. Aalhus, W. M. Robertson, T. A. McAllister, D. J. Gibb, M. E. R. Dugan, N. Aldai, and J. J. McKinnon. 2010. Evaluation of wheat or corn dried distillers' grains with solubles on performance and carcass characteristics of feedlot steers. *Can J. Anim. Sci.* 90:259–269. doi:10.4141/CJAS09089
- Warren, J. G., J. A. Hattey, J. C. Turner, and S. B. Phillips. 2006. Comparison of two micrometeorological methods to determine ammonia volatilization from lagoon swine effluent. *Commun. Soil Sci. Plant Anal.* 37:1339–1356. doi:0.1080/00103620600626825