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Methane emissions, feed intake, and performance of finishing beef cattle offered maize silages harvested at 4 different stages of maturity[1]

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ABSTRACT: This experiment aimed to quantify the methane emissions and intake, digestibility, performance, and carcass characteristics of finishing beef cattle offered maize (*Zea mays*) silages harvested at 1 of 4 sequential stages of maturity and to relate these values to those obtained from animals offered an ad libitum concentrate-based diet. Sixty continental crossbred steers with a mean initial BW of 531 kg (SD 23.8) were blocked (n = 12 blocks) according to BW and allocated from within block to 1 of 5 dietary treatments in a randomized complete block design: maize silage harvested on September 13 (DM = 277 g/kg), maize silage harvested on September 28 (DM = 315 g/kg), maize silage harvested on October 9 (DM = 339 g/kg), maize silage harvested on October 23 (DM = 333 g/kg), and ad libitum concentrates (ALC). Diets based on maize silage were supplemented with 2.57 kg of concentrate DM daily, and ALC diets were supplemented with 1.27 kg of grass silage DM daily. Silage and total DMI were greater ($P = 0.004$) with maize silage harvested on September 28 than with any other treatment, which in turn did not differ. Advancing maize maturity at harvest did not affect BW or carcass gain, with the ALC diet exhibiting greater ($P = 0.036$) rates of carcass gain than any of the maize silage-based treatments. Apparent in vivo digestibility, determined using the AIA indigestible marker technique, was not affected by harvest maturity, with no linear or quadratic trends being identified. Digestibility of DM from the ALC diet was greater ($P < 0.001$) than with any of the maize silage treatments. Starch digestibility did not differ across maize silage maturities; however, a linear ($P = 0.009$) decrease in NDF digestibility was observed. Methane emissions, (g/d) measured using the sulfur hexafluoride tracer technique, were not affected by maize silage maturity. Methane emissions relative to DMI tended ($P = 0.05$) to decline with advancing maize silage maturity, with a similar decline observed when methane was expressed per kilogram of carcass gain. Advancing maize maturity did not result in significant linear or quadratic responses in methane output proportional to GE intake. The ALC diet resulted in less methane output than the maize silage treatments irrespective of the unit of expression. In conclusion, advancing maize harvest maturity did not affect beef cattle performance but reduced methane output relative to DMI and carcass gain. Cattle offered ALC exhibited greater rates of BW gain and less emission of methane compared with cattle offered any of the maize silage treatments.

Key words: cattle, growth, maize (corn), maturity, methane, sulfur hexafluoride

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INTRODUCTION

Methane emissions from enteric fermentation in ruminants have been a cause for concern to the agricultural industry in recent years because of their contribution to global warming (Moss et al., 2000). Methane also represents a loss of energy for the animal, accounting for 0.02 to 0.12 of GE intake (Johnson and Johnson, 1995).

Enteric methane mitigation strategies are required that preferably do not compromise animal performance, with several such strategies reviewed by Boadi et al. (2004) and Beauchemin et al. (2008). Improved animal productivity and dietary manipulation are 2 such strategies that have shown potential for reduced emissions and that at present appear to be the most viable options (Clemens and Ahlgrimm, 2001). Dietary ma-

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nipulation through the increased use of concentrates, specifically increasing the proportion of starch in animal diets, has been associated with decreased daily methane output and also improved animal performance (Lovett et al., 2003). Ensiled maize (*Zea mays*), with its relatively large starch content and increased digestibility, has been reported to improve animal performance relative to grass silage (Mayne and O'Kiely, 2005), with benefits potentially existing in terms of reduced methane production (Beauchemin et al., 2008).

As a crop of maize matures, its starch content increases (Bal et al., 1997) as the grain or ear makes up a greater proportion of the total crop DM. There is a scarcity of published literature regarding the effects of maize maturity at harvest on enteric methane emissions by beef cattle. This experiment quantified the methane emissions and the intake, digestibility, performance, and carcass traits of finishing beef steers offered diets based on maize silages harvested at different maturities and compared these with a high-quality concentrate diet offered for ad libitum consumption.

MATERIALS AND METHODS

All animal procedures used in this study were conducted under experimental license from the Irish Department of Health and Children (Dublin) in accordance with the Cruelty to Animals Act 1876 and the European Communities (Amendment of Cruelty to Animals Act 1876) Regulations 2002 and 2005.

Maize Crop Management, Ensilage, and Characterization

The maize crop (cv. Justina) was sown on April 15, 2006, at a site located at 53°41.7′ N latitude, 6°38.9′ W longitude, and 76.2 m above sea level, and was grown under complete cover plastic mulch as described by Easson and Fearnehough (2000) and Keane (2002). The average harvest date in previous years for maize grown under plastic mulch at this site was October 14. Representative sections of the crop were harvested on September 13 (**MS I**), September 28 (**MS II**), October 9 (**MS III**), and October 23 (**MS IV**) using a precision-chop silage harvester [Claas Jaguar 900 with a 6-row maize header and maize-corn cracker (1.5-mm roll clearance); Claas, Bury St., Edmonds, UK] at a stubble height of 20 to 25 cm. Harvester settings and operation ensured that all grains were fully broken. At each harvest, 60 individual plants (assigned to 6 bundles of 10 plants) were selected at random from the area of the crop being harvested and cut to the same stubble height as that achieved by the forage harvester. From each bundle of 10 plants, the cobs were removed, counted, weighed, and collectively bowl-chopped (MTK 204 Special, Müller, Saarbrücken, Germany), with each bundle of stover similarly weighed and processed. Cob and stover samples were assayed for IVDMD, with each of the cob samples also assayed for starch content. The trailers of maize were weighed and unloaded into horizontal, walled, roofed concrete silos (23.0 m long, 4.3 m wide, and 2.3 m high), where the maize was mechanically compacted (412S JCB, Rocester, Staffordshire, UK). The silos were lined with plastic sheets and the maize was sealed beneath 2 layers of black 0.125-mm polythene sheeting (IS 246 1989). Each maize treatment was harvested, ensiled, and sealed within the same day. Representative samples from each trailer load of forage maize were stored at −18°C until processing, when they were bowl-chopped and composited in chronological groups to produce a total of 6 samples per silo for analysis. Maize silage I, MS II, MS III, and MS IV were ensiled for 216, 201, 190, and 176 d, respectively, before the silos were opened and feed-out commenced. The DM content of MS I to MS IV were 277, 315, 339, and 333 g/kg, respectively.

Assessment of the aerobic stability of each of the silages was carried out using the technique reported by Walsh et al. (2008b). Silage particle size distribution was determined by manual separation, with 20-g samples of each silage (not bowl-chopped) being dried at 40°C for 48 h and manually separated into 5 different lengths (0 to 25 mm, 26 to 50 mm, 51 to 75 mm, 76 to 100 mm, and >100 mm), redried (85°C for 10 h), and then weighed.

Animals and Management

There were 5 dietary treatments in this study, with treatments 1 to 4 (i.e., MS I to MS IV) based on maize silage harvested at the 4 sequential harvest dates, respectively. All maize silages were offered ad libitum and were supplemented with 2.57 kg of concentrate DM/animal, offered separately in a single feed on a daily basis. A fifth treatment, ad libitum concentrates (**ALC**) supplemented with 1.27 kg of grass silage DM/d, was used as a positive control. Animals on the ALC treatment were allowed to adapt to the high-concentrate feeding amount during the first 20 d of the experimental period. Fresh drinking water was available continually to all animals.

Animals were sourced from commercial beef farms and offered grass silage for several months before the experimental period. All animals were treated for internal parasites (Trodax 34%, Merial Animal Health Ltd., Buckinghamshire, UK; Qualimec Solution for injection, Janssen Animal Health, Wycombe, UK) and skin lice [deltamethrin 0.75% (wt/vol); Butox Pour-On, Intervet Productions S.A., Igoville, France] and were vaccinated against infectious bovine rhinotracheitis and parainfluenza (Bovilis, Intervet Ireland Ltd., Dublin, Ireland) before the experiment. Sixty continental crossbred steers, with a mean initial BW of 531 kg (SD 23.8), were selected and weighed, unfasted, on 2 consecutive days at the beginning of the experiment, with the average of these 2 BW taken as the initial BW. Animals were assigned to 1 of 12 replicate blocks on a descending BW basis and were randomly allocated from

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within block to the 5 dietary treatments. Animals were housed in a slatted-floor shed with 2 pens of 5 animals per treatment, with the remaining 2 animals from each maize treatment penned in 2 pens of 4 animals. The 2 remaining animals from the ALC treatment were in a 13th pen together with 2 nonexperimental animals offered the same diet. This allowed all treatments to have the same lying area (2.73 m^2/animal), with pens within treatment located within different parts of the shed to ensure an even distribution of treatments throughout the shed. All animals had continuous access to clean, fresh drinking water. Animals were individually offered their respective diets through electronically controlled Calan doors (American Calan Inc., Northwood, NH), with maize silage weighed out of the silo and offered to each animal in a single feed each morning. Refused feed was recorded daily for each individual animal and was discarded twice weekly, with ad libitum access being based on approximately 1.1 times the intake of the previous day. The DM content of refused feed was assumed to be the same as the offered feed. Samples of maize silage and grass silages offered to cattle were taken on 3 d/wk and stored at −18°C before being mixed and bowl-chopped in groups representing 3 consecutive weeks. Concentrate samples were obtained once weekly and composited as with silage samples and stored at −18°C until processing.

Body weights were recorded before the morning feeding every 21 d, with daily BW gain calculated as the difference between final and initial BW divided by the number of days the experimental diets were offered. Fresh feed intake was recorded daily, with the DMI calculated for each silage using the DM corrected for volatiles lost during oven drying. A 51% dressing percentage of 510 g of carcass/kg of BW was assumed to estimate initial carcass weight (Caplis et. al., 2005). Animals were slaughtered over 2 consecutive days (6 blocks per day) at the end of the experimental period (d 109 and 110) at a commercial abattoir. Cold carcass weights were recorded, with carcass conformation and fat scores graded using a video-imaging analysis carcass classification system (VBS 2000, E + P, Oranienberg, Germany) based on the European Union Beef Carcass Classification Scheme (EUROP scale; Commission of the European Communities, 1982). Perinephric and retroperitoneal fat was removed from both sides of the carcass and weighed. Carcass gains were estimated as the difference between initial and final carcass weights, with final dressing percentage determined by dividing the cold carcass weight by the final BW. Feed conversion efficiency (**FCE**) was expressed as kilograms of carcass gain/1,000 kg of DMI.

Methane Measurement and Blood Sampling

Methane emissions were measured using the sulfur hexafluoride (**SF_6**) tracer technique (Johnson et al., 1994). Each animal underwent methane sampling once during the experimental period. There were 4 methane sampling periods during this study, with 3 different animals from each treatment sampled during each period. Animals from blocks 1 to 3, 4 to 6, 7 to 9, and 10 to 12 were sampled on d 24 to 28, d 52 to 56, d 80 to 84, and d 94 to 98, respectively. Animals were tethered in individual stalls in a separate facility to allow operation of the SF_6 technique, but with their individual dietary management unchanged. Tethering occurred 6 d before sampling to allow DMI to stabilize after the temporary move to the sampling facility. A brass permeation tube containing SF_6 gas, with a predetermined mean release rate of 1.8 mg of SF_6/d (SD 0.39), was administered to each of the 15 animals (3 animals per treatment) within a period 6 d before methane collection, thereby allowing the tracer gas to equilibrate in the rumen. Animals were fitted with gas collection halters, with each halter connected to a preevacuated polyvinyl chloride collection canister designed to fill to one-half over a 24-h period, with each 24-h collection commencing at 0700 h daily. Canisters were hung above the animals to avoid damage and were connected to the halters with plastic peak tubing inside an air-line flexi-coil tube. To correct the animal values for background atmospheric concentrations of methane and SF_6 adjacent to the animals, gas samples were collected from the ambient air in the sampling facility. After gas collection, the pressure readings were recorded to determine the gas dilution factor, and pure N was used to pressurize each canister to 1,250 hPa before a sample was taken from each for analysis.

Methane outputs (g/d) proportional to GE intake (MJ/d), DMI (kg/d), and carcass gain (g/d) were calculated by dividing the daily methane output of each animal by their daily GE intake and DMI (during methane sampling) and carcass gain (throughout the entire experimental period), respectively. Blood samples were collected on the final day of each methane sampling period from each of the animals assigned to methane sampling. Samples were obtained via jugular venipuncture into 9-mL evacuated vials (Greiner Vacuette, Cruinn Diagnostics, Dublin, Ireland) containing lithium heparin as an anticoagulant, immediately before feeding (0830 h) and at 2 and 6 h postfeeding, with the mean value for each animal used for statistical analyses.

Digestibility Measurement

Whole-tract digestibility was estimated using the indigestible AIA marker technique, as described by Van Keulen and Young (1977). Each animal was used once for in vivo digestibility determination. There were 4 measurement periods, with 3 different animals from each treatment assigned to each period. Animals from blocks 1 to 3, 4 to 6, 7 to 9, and 10 to 12 were sampled on d 31 to 35, d 59 to 63, d 87 to 91, and d 101 to 105, respectively. Representative samples of each offered silage and concentrate were obtained daily, in duplicate, stored at −18°C, and composited appropriately at the end of the 5-d sampling period. A representative sam-

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ple of silage refusals was obtained from each animal daily (excluding those animals on the ALC treatment because no silage refusals occurred), with a sample of concentrate refusals obtained from each of the animals offered ALC. Samples of feed were composited at the end of the sampling period, resulting in 1 sample/animal. Refusals were discarded daily after sampling. Fecal grab samples were obtained (200 g/animal) daily for 5 d, before feeding, by rectal palpation. They were pooled at the end of the sampling period, thus producing 1 composite sample/animal.

Chemical Analyses

Preensiled forage samples were dried in an oven with forced-air circulation at 98°C for 16 h for DM determination, with all composited silages dried at 85°C for 16 h and corrected for loss of volatiles using the equation of Porter and Murray (2001). All concentrate samples were oven-dried at 98°C for 16 h for DM determination, with subsamples of silages and concentrates for subsequent analysis oven-dried at 40°C for 48 h. Fecal DM content was determined by oven drying at 98°C for 48 h, with samples for subsequent analysis dried at 40°C for 48 h. Subsamples of each silage, concentrate, and fecal sample were milled through a 1-mm screen (Wiley mill, Arthur H. Thomas, Philadelphia, PA) before chemical analysis. Determination of IVDMD and in vitro OM digestibility were carried out using the technique of Tilley and Terry (1963), which was modified so that the final residue was isolated by filtration (Whatman GFA55mm, Whatman International, Maidstone, UK) rather than centrifugation. The NDF and ADF contents were determined according to the method of Van Soest et al., (1991), with ash content determined by complete combustion in a muffle furnace at 550°C for 5 h. The CP (N × 6.25) content was determined using a Leco FP 428 N analyzer (St. Joseph, MI) based on AOAC (1990) method 990-03, with starch content determined according to the method of Mc Cleary et al. (1997). Concentration of water-soluble carbohydrates was determined using the anthrone method (Thomas, 1977). Gross energy was determined by bomb calorimetry (6300 Isoperibol Calorimeter, Parr Instruments, Moline, IL), and for silage samples, polythene was used as a primer to ensure complete combustion of the undried material (Porter, 1992). Feed ME concentrations were calculated using Eq. 142 of AFRC (1993). Feed and fecal AIA concentrations were determined using the method described by Van Keulen and Young (1977).

Aqueous extracts were obtained from fresh samples (200 g) of each of the silages by mechanical compaction using a hydraulic press. The pH of the aqueous extracts was measured using an Orion digital pH meter (model 420 pH meter and electrode, Thermo Orion, Thermo Fisher Scientific, Waltham, MA). The concentrations of VFA (acetic, butyric, and propionic) in the silage extracts were measured using an automated gas chromatograph (Shimadzu GC-8A, Shimadzu Corporation, Kyoto, Japan) following the method described by Ranfft (1973). Lactic acid concentration was analyzed using an SP-Ace Clinical Chemical Analyzer (Schiapparelli Biosystems Inc., Fairfield, NJ) and an L-lactic acid UV-method test kit (catalog number 101309084035, Boehringer Mannheim/R-Biopharm, Darmstadt, Germany), with D-lactate determined using the enzyme D-lactate dehydrogenase (catalog number 1016941001, Boehringer Mannheim/R-Biopharm). Concentrations of NH_3 were determined using the SP-Ace Clinical Chemical Analyzer and the Thermo Electron Infinity ammonia liquid stable reagent kinetic method (Thermo Electron, Waltham, MA).

Concentrations of SF_6 and methane in animal breath, as well as in the ambient air, were determined by gas chromatography (GC model 3800, Varian BV, Middelburg, the Netherlands), with each canister sampled in duplicate. Gaseous methane concentration was determined using a flame-ionization detector and stainless steel 0.3 cm × 1.2 m Porapack N column, 80 to 100 mesh (Varian BV), with SF_6 concentration determined using an electron capture detector with a stainless steel column, 0.3 cm × 1.8 m, packed with a molecular sieve (5A) of 40 to 60 mesh (Varian BV; Lovett et al., 2003). The rate of methane production was calculated using the following equation: CH_4 (g/d) = SF_6 release rate (g/d) × [CH_4 (μg/m^3)]/[SF_6 (μg/m^3)] (Johnson et al., 1994). Blood samples were centrifuged at 2,000 × g (15 min at 4°C), with the plasma stored at −20°C. The plasma urea concentration analyzed using an Olympus AU 400 Clinical Analyzer (kinetic urease method, catalog method OSR6134, Olympus, Shizouka, Japan).

Statistical Analyses

One animal was removed from the study for reasons unrelated to the dietary treatment, resulting in data from 59 animals being analyzed. Mean (SD) preensiling and postensiling chemical composition variables were calculated for each of the maize silages. Normality of data distribution was determined using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC). All data were subjected to 2-way ANOVA using the MIXED procedure of SAS. Animal intake and performance data were analyzed according to the following statistical model: $Y_{ij} = \mu + D_i + B_j + e_{ij}$, where Y_{ij} is the variable under consideration, μ is the overall mean, D_i is the fixed effect of diet, B_j is the fixed effect of block, and e_{ij} is the associated error. Methane, blood, and digestibility data were analyzed according to the model $Y_{ijk} = \mu + D_i + B_j + P_k + e_{ijk}$, where μ, D_i, and B_j are as described previously, P_k is the fixed effect of sampling period, and e_{ijk} is the associated error. There was no evidence ($P = 0.51$) of a treatment × sampling period interaction; thus, this term was not included in the final statistical model.

Treatments were separated using least squares means and were detected using the PDIFF procedure of SAS. Linear and quadratic contrasts were carried out within

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the maize treatments to determine the effects of advancing maturity at harvest on the variables of interest.

RESULTS

Plant, Silage, Concentrate, and Diet Characteristics

Mean DM yields (±SD) for MS I to MS IV were 12.9 (1.45), 14.7 (1.66), 15.7 (2.61), and 14.8 (2.70) t/ha respectively. No effluent was released from the maize silages. As crop development progressed, the DM content of both the cob and stover fractions at harvest increased numerically (Table 1). Simultaneously, starch concentration in the cob fraction increased from MS I to MS III, with stover digestibility declining with later harvesting. As maize crop maturity progressed, whole-crop maize silage DM concentration increased from MS I to MS III, with a similar trend found with starch content (Table 2). Conversely, silage NDF and ADF concentrations decreased, with the most marked changes in these components occurring between MS I and MS II. Silage CP, IVDMD, ash, and water-soluble carbohydrates did not differ markedly among maize silage-based treatments. All maize silages were considered well preserved, as evidenced by the low pH and the increased concentration of lactic acid as a proportion of the total fermentation products. The mean chemical compositions of the concentrates are presented in Table 3. The chemical compositions of each of the experimental diets are presented in Table 4. All the maize silages were equally prone to aerobic deterioration (Table 5). However, management practices at feed-out prevented noticeable deterioration. Particle size distribution was similar across all 4 maize silages, whereas the grass silage had a greater proportion of particles in the larger size categories.

Feed and Energy Intake

Advancing maize maturity at harvest resulted in a quadratic response ($P = 0.002$) in silage DMI, with MS II having greater silage and total DMI ($P = 0.004$) than any of the other maize silages (Table 6). No differences in silage or total DMI were observed between the other maize treatments. Consequently, steers offered MS II had a greater ($P = 0.027$) ME intake than those offered the other maize silage. Steers offered ALC had less total DMI ($P = 0.002$) than those offered MS II but were not different from any other treatment, with intake of ME from the ALC-based diet being similar to that of MS II and greater ($P = 0.002$) than that of MS I, MS III, or MS IV. Intake of GE was greater ($P = 0.009$) with MS II than MS I or MS III and tended ($P = 0.07$) to be greater than that of MS IV. No differences were observed between the other maize harvests. Cattle offered ALC had GE intakes similar to those offered MS II but were greater ($P = 0.020$) than those offered the other maize silage treatments.

Table 1. Chemical composition of the preensiled harvested maize plant components (±SD)[1]

	Cob fraction				Stover fraction			
Item	I	II	III	IV	I	II	III	IV
Proportion (DM basis)	0.57 ± 0.020	0.55 ± 0.003	0.63 ± 0.002	0.63 ± 0.003	0.43 ± 0.002	0.45 ± 0.003	0.37 ± 0.002	0.37 ± 0.003
DM, g/kg	412 ± 20.9	500 ± 17.5	517 ± 6.5	531 ± 6.9	184 ± 5.7	222 ± 13.3	229 ± 8.2	233 ± 14.6
Composition of DM								
IVDMD, g/kg	822 ± 46.8	823 ± 32.5	840 ± 15.6	821 ± 16.4	671 ± 20.5	638 ± 25.1	606 ± 17.6	584 ± 12.6
Ash, g/kg of DM	18 ± 1.3	16 ± 0.6	16 ± 1.1	17 ± 0.6	50 ± 3.7	57 ± 6.1	55 ± 2.5	54 ± 2.5
Starch, g/kg of DM	535 ± 23.0	575 ± 55.1	618 ± 28.5	603 ± 20.1	ND[2]	ND	ND	ND

[1]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23.
[2]ND = not determined.

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Table 2. Chemical composition of maize and grass silages at feed-out (±SD)

	Maize harvest[1]				
Item	I	II	III	IV	GS[2]
DM,[3] g/kg	277 ± 13.3	315 ± 7.2	339 ± 6.8	333 ± 10.2	253 ± 14.0
Composition of DM, g/kg of DM unless otherwise stated					
IVDMD, g/kg	710 ± 17.8	723 ± 13.8	734 ± 22.0	715 ± 13.9	749 ± 12.0
IVOMD,[4] g/kg	708 ± 11.2	726 ± 11.8	736 ± 18.9	718 ± 11.6	756 ± 14.7
NDF	485 ± 13.8	447 ± 17.3	437 ± 16.5	434 ± 11.8	566 ± 19.8
ADF	279 ± 10.3	250 ± 8.4	229 ± 8.1	233 ± 4.0	ND[5]
AIA[6]	7.4 ± 1.02	6.14 ± 0.99	5.1 ± 0.72	5.7 ± 0.36	4.8 ± 1.70
Ash	36 ± 1.8	36 ± 2.1	33 ± 2.6	34 ± 1.6	81 ± 2.2
CP	88 ± 2.6	89 ± 3.5	92 ± 5.1	93 ± 2.6	141 ± 2.8
Starch	315 ± 20.3	362 ± 13.2	381 ± 17.8	386 ± 14.9	ND
Water-soluble carbohydrates	8.8 ± 0.78	11.1 ± 0.62	10.5 ± 1.08	9.3 ± 0.32	ND
ME,[7] MJ/kg of DM	10.7 ± 0.2	11.0 ± 0.2	11.3 ± 0.3	10.9 ± 0.2	11.9 ± 0.2
GE, MJ/kg of DM	19.9 ± 2.13	18.9 ± 0.56	18.7 ± 0.75	19.6 ± 0.51	21.0 ± 1.84
Fermentation characteristics, g/kg of volatile corrected DM unless otherwise stated, except pH					
pH	4.01 ± 0.05	3.89 ± 0.14	3.86 ± 0.08	4.01 ± 0.05	3.92 ± 0.03
Lactic acid (D + L)	31 ± 9.9	49 ± 10.5	53 ± 5.9	49 ± 3.1	109 ± 14.9
D-Lactic acid[8]	0.54 ± 0.003	0.49 ± 0.002	0.49 ± 0.001	0.47 ± 0.003	0.47 ± 0.003
Ethanol	1.3 ± 0.57	0.7 ± 0.32	0.8 ± 0.29	1.2 ± 0.35	1.5 ± 0.31
Acetic acid	5.0 ± 0.69	1.5 ± 0.96	2.2 ± 0.26	2.8 ± 0.65	5.1 ± 0.42
Propionic acid	0.9 ± 0.20	0.3 ± 0.09	0.3 ± 0.16	0.4 ± 0.17	0.2 ± 0.07
Butyric acid	0.2 ± 0.09	0.1 ± 0.09	0.2 ± 0.16	0.2 ± 0.12	1.2 ± 0.18
Lactic acid/total fermentation products	0.80 ± 0.065	0.95 ± 0.021	0.94 ± 0.013	0.92 ± 0.021	0.93 ± 0.004
NH_3, g/kg of total N	74 ± 8.5	73 ± 12.5	78 ± 10.3	89 ± 8.0	ND

[1]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23.
[2]Grass silage, 1.27 kg of DM offered as supplement to cattle offered concentrates ad libitum.
[3]Corrected for loss of volatiles during oven drying.
[4]OM digestibility, measured in vitro.
[5]ND = not determined.
[6]Based only on samples obtained during digestibility determination.
[7]Estimated based on IVOMD (AFRC, 1993).
[8]D-Lactic acid as proportion of total lactic acid.

Table 3. Ingredient and chemical composition of the concentrates (±SD)[1]

Item	MS-concentrate	ALC-concentrate
Ingredient, g/kg, as-fed basis		
Rolled barley	600	830
Soybeans (dehulled, solvent extracted)	330	100
Sugarcane molasses	50	50
Mineral and vitamin premix[2]	20	20
Chemical composition, g/kg of DM unless stated otherwise		
DM, g/kg	858 ± 6.1	836 ± 7.2
IVDMD, g/kg	877 ± 15.2	868 ± 12.3
IVOMD,[3] g/kg	876 ± 10.6	865 ± 10.1
AIA[4]	2.7 ± 0.37	1.9 ± 0.24
Ash	72 ± 12.5	63 ± 5.9
Starch	308 ± 35.8	442 ± 9.0
NDF	160 ± 9.4	160 ± 13.5
CP	268 ± 30.7	160 ± 5.6
ME,[5] MJ/kg of DM	12.8 ± 0.03	12.7 ± 0.08
GE, MJ/kg of DM	19.5 ± 0.24	19.5 ± 0.36

[1]MS-concentrate = maize silage-concentrate diet (maize silage supplemented with 2.57 kg of concentrate DM/animal daily); ALC-concentrate = ad libitum concentrate diet (ad libitum concentrates plus 1.27 kg of grass silage DM/animal daily).
[2]Premix supplied per kilogram of concentrate: 10,000 IU of vitamin A, 2,000 IU of vitamin D_3, 50 IU of vitamin E as α-tocopherol acetate, 0.50 mg of Se as sodium selenite, 10 mg of Cu as cupric sulfate, and 10 mg of Cu as cupric chelate of AA hydrate.
[3]OM digestibility, measured in vitro.
[4]Based only on samples obtained during digestibility determination.
[5]Estimated based on AFRC (1993; Eq. 142).

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Table 4. Chemical composition of the maize silage and ad libitum concentrate (ALC)[1] diets

Diet composition, g/kg of DM unless stated otherwise	Maize harvest[2]				
	I	II	III	IV	ALC
Starch	313	350	364	368	369
CP	131	127	133	134	157
NDF	408	385	373	370	227
Ash	45	44	42	43	66
ME, MJ/kg of DM	11.2	11.4	11.6	11.3	12.6
GE, MJ/kg of DM	19.8	19.0	18.9	19.6	19.7

[1]Ad libitum concentrates plus 1.27 kg of grass silage DM/animal daily.
[2]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23; maize silage supplemented with 2.57 kg of concentrate DM/animal daily.

Animal Performance, Carcass Traits, FCE, and Plasma Urea

Daily BW gain was not altered by advancing maize harvest maturity (Table 6). The BW gain of steers offered ALC did not differ ($P = 0.18$) from those offered MS II but was greater ($P = 0.036$) than those offered the other treatments. Final BW increased ($P = 0.040$) from MS I to MS II, whereas MS III and MS IV were not different from either treatment. Final BW was greater ($P = 0.046$) for ALC than for all other treatments except MS II ($P = 0.23$). Dressing percentage was not affected by dietary treatment. The ALC diet exhibited greater ($P = 0.042$) carcass weights than any of the maize silage-based treatments, which in turn were not different from each other. Advancing maize harvest maturity did not result in a difference in the rate of daily carcass gain, with all maize silage-based treatments exhibiting less ($P = 0.036$) carcass gain than steers offered ALC. A linear improvement ($P = 0.034$) in carcass conformation score was identified in response to advancing maize harvest date. Cattle offered ALC exhibited carcass conformation scores similar to those offered maize silage-based treatments. Perinephric plus retroperitoneal fat was less ($P = 0.045$) for the MS III treatment than for the other maize silage treatments, with the ALC treatment being intermediate.

Feed conversion efficiency, assessed on a carcass gain basis, was less ($P = 0.046$) for MS II than MS IV, with steers offered ALC having greater ($P = 0.027$) rates of FCE than those offered any of the maize silage-based treatments. No significant effects of dietary treatment were identified for dressing percentage ($P = 0.19$) or for BW ($P = 0.31$) or carcass gains ($P = 0.29$) expressed relative to ME intake. Data regarding plasma urea were not found to be normally distributed, so log-transformations were carried out. Plasma urea concentration was not affected by maize maturity at harvest, with cattle offered ALC displaying a greater ($P < 0.001$) concentration than those offered any of the maize silage-based treatments.

Apparent Diet Digestibility

Apparent in vivo DM digestibility of the maize silage diets was not affected by maize maturity at harvest (Table 7). Digestibility of the DM fraction was greater ($P < 0.001$) for ALC than for any of the maize silage treatments. Starch digestibility did not differ across the different maize maturities. Furthermore, the starch

Table 5. Particle length and aerobic stability and deterioration indices of the maize and grass silages (±SD)

Item	Maize harvest[1]				
	I	II	III	IV	GS[2]
Particle length, g of DM/kg of DM					
0 to 25 mm	904 ± 30	897 ± 41	887 ± 35	891 ± 35	258 ± 73
26 to 50 mm	69 ± 35	65 ± 26	62 ± 12	64 ± 29	337 ± 27
51 to 75 mm	15 ± 8	20 ± 11	26 ± 18	17 ± 9	174 ± 30
76 to 100 mm	6 ± 5	14 ± 11	20 ± 17	21 ± 18	89 ± 23
>100 mm	6 ± 6	4 ± 3	5 ± 7	8 ± 6	142 ± 53
Aerobic stability and deterioration indices					
Hours to temperature increase >2°C	13 ± 6.6	12 ± 10.1	18 ± 4.7	15 ± 11.4	53 ± 17.5
Maximum temperature increase, °C	22 ± 0.4	21 ± 3.4	24 ± 0.9	23 ± 1.2	19 ± 1.3
Hours to maximum temperature increase	32 ± 9.3	37 ± 15.4	32 ± 2.1	27 ± 10.5	192 ± 4.4
Accumulated temperature increase to 120 h, °C	84 ± 7.0	92 ± 27.5	97 ± 5.0	92 ± 10.7	22 ± 6.1
Accumulated temperature increase to 192 h, °C	126 ± 8.8	162 ± 56.8	176 ± 5.0	157 ± 13.5	67 ± 11.6

[1]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23.
[2]Grass silage.

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Table 6. Feed intake, performance, carcass traits, feed conversion efficiency, and plasma urea of finishing steers offered maize silage and ad libitum concentrate (ALC)[1] diets

	Maize harvest[2]						*P*-value		
Item	I	II	III	IV	ALC	SEM[3]	Treatment[4]	Linear[5]	Quadratic[5]
Feed intake									
Silage intake, kg of DM/d	8.31[b]	9.38[a]	8.56[b]	8.49[b]	1.83[c]	0.171	<0.001	0.71	0.002
Total DMI,[6] kg/d	10.88[b]	11.95[a]	11.13[b]	11.06[b]	11.03[b]	0.186	0.003	0.74	0.005
ME intake, MJ/d	122.1[c]	135.8[a]	129.2[b]	124.5[bc]	138.0[a]	1.99	<0.001	0.94	<0.001
GE intake, MJ/d	213[c]	228[ab]	211[c]	218[bc]	231[a]	3.8	0.002	0.89	0.27
CP intake, kg/d	1.43[c]	1.53[b]	1.48[bc]	1.49[b]	1.84[a]	0.022	<0.001	0.15	0.030
Performance, feed conversion ratio, and plasma urea									
Beginning BW, kg	530	531	531	531	530	0.8	0.44	0.30	0.14
Final BW, kg	663[c]	681[ab]	669[bc]	674[bc]	691[a]	5.8	0.015	0.40	0.28
BW gain, g/d	1,208[b]	1,353[ab]	1,246[b]	1,298[b]	1,455[a]	51.4	0.014	0.48	0.37
Dressing percentage, g/kg	548	536	551	547	552	4.8	0.19	0.56	0.37
Carcass weight, kg	363[b]	365[b]	368[b]	369[b]	381[a]	4.2	0.038	0.29	0.90
Carcass gain, g/d	844[b]	849[b]	881[b]	887[b]	1,002[a]	37.3	0.033	0.34	0.98
Conformation score[7]	2.75	2.73	2.92	3.08	2.92	0.120	0.26	0.034	0.46
Fat score[8]	3.42	3.34	3.33	3.42	3.83	0.144	0.10	0.99	0.59
PRF,[9] kg	8.65	8.72	6.83	8.60	8.20	0.490	0.05	0.36	0.09
PRF, g/kg of carcass	23.9[a]	24.2[a]	18.5[b]	23.4[a]	21.5[ab]	1.44	0.044	0.27	0.12
Feed conversion efficiency [10]	77.8[bc]	70.6[c]	79.1[bc]	80.6[b]	91.5[a]	3.34	0.003	0.26	0.21
BW gain/ME intake, g/MJ	9.9	9.9	9.6	10.4	10.5	0.31	0.23	0.35	0.22
Carcass gain/ME intake, g/MJ	6.9	6.2	6.8	7.2	7.2	0.29	0.14	0.33	0.08
Plasma urea,[11] mmol/L	1.43[b] (4.23)	1.37[b] (4.00)	1.36[b] (3.99)	1.49[b] (4.52)	1.90[a] (6.74)	0.048	<0.001	0.40	0.06

[a–c]Within a row, means without a common superscript differ ($P < 0.05$).
[1]Ad libitum concentrates plus 1.27 kg of grass silage DM/animal daily.
[2]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23; maize silage supplemented with 2.57 kg of concentrate DM/animal daily.
[3]For n = 12/treatment.
[4]Overall treatment effect.
[5]Linear and quadratic effects of advancing maize maturity at harvest.
[6]Ad libitum intake determined over the entire duration of the study.
[7]European Union Beef Carcass Classification Scheme (EUROP): scale of 1 (poorest = P) to 5 (best = E).
[8]European Union Beef Carcass Classification Scheme: scale 1 (fattest) to 5 (leanest).
[9]Perinepheric + retroperitoneal fat.
[10]Kilograms of carcass gain/1,000 kg of DMI.
[11]Log-transformed values (untransformed values in parentheses).

Table 7. In vivo apparent digestibility of the total diets

Item	Maize harvest[1]				ALC[2]	SEM[3]	*P*-value		
	I	II	III	IV			Treatment[4]	Linear[5]	Quadratic[5]
Total DMI,[6] kg/d	10.37[b]	12.21[a]	11.02[b]	11.07[b]	11.10[b]	0.298	0.004	0.51	0.005
In vivo apparent digestibility									
DM	0.71[b]	0.69[b]	0.70[b]	0.68[b]	0.83[a]	0.012	<0.001	0.15	0.95
Starch	0.99[ab]	0.98[b]	0.98[b]	0.98[b]	0.99[a]	0.003	0.049	0.16	0.44
CP	0.62[b]	0.57[c]	0.60[bc]	0.58[c]	0.76[a]	0.015	<0.001	0.09	0.36
NDF	0.55[b]	0.50[bc]	0.49[bc]	0.46[c]	0.65[a]	0.021	<0.001	0.009	0.62
Starch plus NDF	0.74[b]	0.73[b]	0.74[b]	0.72[b]	0.87[a]	0.012	<0.001	0.53	0.93

[a–c]Within a row, means without a common superscript differ ($P < 0.05$).
[1]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23; maize silage supplemented with 2.57 kg of concentrate DM/animal daily.
[2]Ad libitum concentrates plus 1.27 kg of grass silage DM/animal daily.
[3]For n = 12/treatment.
[4]Overall treatment effect.
[5]Linear and quadratic effects of advancing maize maturity at harvest.
[6]Ad libitum intake during digestibility determination only.

component of the ALC diet had a digestibility similar to that of MS I. Apparent digestibility of the CP fraction of the diet was numerically greatest for MS I, with a tendency for a linear decrease ($P = 0.09$) with later harvesting. Digestibility of the NDF fraction of the total diets was also greatest for MS I, with a linear decrease ($P = 0.009$) identified as maturity advanced. Digestibility of starch plus NDF did not differ across the maize silage-based treatments, whereas the ALC diet had a greater ($P < 0.001$) value than any of the maize silage treatments. The ALC diet exhibited greater CP ($P < 0.001$) and NDF ($P = 0.001$) digestibility values than any of the maize silage treatments.

Methane Emissions

Total daily methane output was not affected by maize maturity at harvest (Table 8). However, steers offered ALC exhibited reduced ($P < 0.001$) methane output per day when compared with those offered maize silage-based diets. Advancing maize harvest maturity led to a reduction (linear, $P = 0.05$) in methane emissions when expressed relative to DMI during the sampling periods. The ALC-based diet led to reduced ($P = 0.005$) rates of methane emission per kilogram of DMI compared with any of the maize silage-based treatments. Advancing maize harvest maturity did not result in a clear response pattern when methane output was expressed as a proportion of GE intake; however, the tendency for MS IV to be less than MS I ($P = 0.07$) suggests a numerical trend of decreasing methane losses with advancing maturity. Methane, as a percentage of GE intake, was less ($P = 0.029$) for ALC than for MS I, MS II, or MS III, but did not differ ($P = 0.10$) from that of MS IV. When methane emissions were expressed relative to carcass gain, output tended to decrease linearly ($P = 0.06$) with advancing maturity at harvest. Steers offered the ALC diet had less ($P = 0.017$) emission of methane per kilogram of carcass gain compared with those offered maize silage-based diets.

DISCUSSION

Silage Characteristics

In diets based on maize silage, the starch content and digestibility of the plant are important factors affecting nutritional quality. All maize silages in this study had starch contents greater than 300 g/kg of DM, with nutritive values similar to good-quality crops grown under commercial conditions in Ireland (Burke et al., 2007). The crop harvested on September 13 was more mature than would normally be observed in early September, and the scale of subsequent change in silage chemical composition was thus less than normal (Little et al., 2005). Particle size distribution of the silages was similar across all maize silage treatments, and all were coarsely chopped relative to values reported by Bal et al. (2000) and Soita et al. (2005). Although each of the maize silages was aerobically unstable under standard test conditions, the prevailing management prevented this from being evident in practice, so their feeding value was not compromised.

Feed and Energy Intake, Diet Digestibility, and Plasma Urea

Intakes of DM by animals offered maize silage-based diets were comparable with the values obtained by Browne et al. (2004) for maize silage of similar chemical composition. In the present study, DMI was calculated using the DM content of only the feeds offered, and this may be important to consider when interpreting the DMI data. The significantly greater intakes of silage and total DM associated with MS II were consistent over the entire duration of the study, with no differences observed between the other treatments. The reasons for the increased DMI with MS II are unclear because factors that typically affect intake, such as DM content, DM digestibility, fermentation characteristics (Browne et al., 2004), or particle length, were not markedly dif-

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Table 8. Methane (CH_4) emissions from finishing cattle offered maize silage and ad libitum concentrate (ALC)[1] diets

	Maize harvest[2]						*P*-value		
Item	I	II	III	IV	ALC	SEM[3]	Treatment[4]	Linear[5]	Quadratic[5]
CH_4, g/d	301[a]	304[a]	301[a]	284[a]	228[b]	21.2	<0.001	0.26	0.33
CH_4, g/kg of DMI	29.4[a]	25.8[b]	27.7[ab]	26.2[b]	22.1[c]	1.81	<0.001	0.05	0.26
CH_4, % of GE intake	8.4[a]	7.7[a]	8.1[a]	7.3[ab]	6.3[b]	0.40	0.016	0.13	0.98
CH_4, g/kg of carcass gain	354[a]	354[a]	311[a]	314[a]	236[b]	18.1	<0.001	0.06	0.92

[a–c]Within a row, means without a common superscript differ ($P < 0.05$).
[1]Ad libitum concentrates plus 1.27 kg of grass silage DM/animal daily.
[2]Harvest dates: I = September 13; II = September 28; III = October 9; IV = October 23; maize silage supplemented with 2.57 kg of concentrate DM/animal daily.
[3]For n = 12/treatment.
[4]Treatment significance effect.
[5]Linear and quadratic effects of advancing maize maturity at harvest.

ferent for this treatment compared with any of the other maize silage treatments. Consequently, intakes of GE and ME were greatest for MS II primarily because of the greater silage DMI associated with this treatment.

Total DMI for animals offered ALC were in accordance with those reported by McGee et al. (2006) for comparable cattle offered a similar barley-based ration. The absence of a difference in total DMI between the maize silage and ALC diets concurs with the findings of Walsh et al. (2008a).

In accordance with earlier studies (Johnson et al., 1999; Di Marco et al., 2002), advancing maize maturity at harvest did not significantly affect apparent DM digestibility despite a decline in vivo NDF digestibility. Grant and Mertens (1992) attributed such a decline in NDF digestibility to the negative associative effects of greater starch intake on fiber digestion. The digestibility of the starch component of the diet was almost complete for all treatments, in agreement with the results of Cammell et al. (2000) and Browne et al. (2005). This indicates that the starch in the maize silages was as accessible as the starch in the rolled barley in the supplementary and ALC concentrates. Clearly, the effective use of the corn cracker on the forage harvester ensured breakage of the maize kernels and thus the complete availability of the starch therein. The greater CP digestibility of the least mature maize agrees with the report of Calder et al. (1977), who found a negative effect of maize maturity on N digestibility.

The suitability of the AIA technique for digestibility determination in cattle offered high-concentrate diets may be somewhat limited, as suggested by Thonney et al. (1985). The reduced silica content of high-concentrate diets, with silica being one of the main components of AIA, can lead to increased variability in digestibility estimates. However, sampling a large number of animals over several days, as in the present study, can reduce the variation associated with this type of diet, as suggested by Sales and Janssens (2003).

All plasma urea values observed in this study fell within the normal range (3.4 to 7.3 mmol/L; Castejon and Leaver, 1994) and are indicative of an appropriate balance between rumen available N and ruminally fermented energy across the diets used. The absence of an effect of maize harvest date on plasma urea concentration is somewhat surprising. The greater DMI observed with MS II would imply a greater intake of CP, but a corresponding elevation in plasma urea was not observed. The concentration of plasma urea observed with the ALC diet was greater than observed with the maize silage treatments, in agreement with the report by Walsh et al. (2008b), and is a reflection of the greater CP intake that was observed with ALC. Previous studies by Walsh et al. (2008b) and Owens et al. (2009) involving diets similar to the present study reported suboptimal rumen ammonia values when maize silage-based diets were offered to steers. However, the plasma urea values recorded in the present study suggested that such an apparent deficiency was not repeated here.

Animal Performance, FCE, and Carcass Traits

Greater rates of BW gain were obtained with the MS I to MS IV treatments compared with the values predicted using Ministry of Agriculture, Fisheries and Food (1984) values (1,208, 1,353, 1,246, and 1,298 g/d vs. 1,070, 1,226, 1,172, and 1,110 g/d, respectively). This is possibly a reflection of the greater DM digestibility and energy content of each of the maize silage-based diets in this study, as well as the growth potential of the animals used. All maize silage treatments supported a rate of BW gain of greater than 1.0 kg/d, which was the maximum herd-average BW gain reported by Buckley et al. (1998) in a study of commercial finishing strategies for continental beef cattle on a sample of Irish farms. An implication of this is that adoption of maize silage-based feeding regimens by commercial producers in Ireland could potentially result in shorter finishing periods and reduced feeding costs.

The absence of an effect of maize maturity at harvest on cattle growth rate may be due to the relatively narrow range of starch contents and in vivo DM digestibil-

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ity values of the maize silage in the present study. It is surprising that despite greater DM and ME intakes for MS II, no improvement in BW or carcass weight gains were observed. The rate of BW gain for this treatment was numerically greater than for the other maize silage treatments, but this difference was not significant. The reasons for this are unclear, but animals on this treatment may have had a greater rumen fill, and this is suggested by the numerically smaller dressing percentage for MS II. Ultimately, the absence of an effect of maize maturity at harvest on carcass weight gain reflects the lack of significant differences in BW gain. Other studies (Calder et al., 1977; Browne et al., 2004) have also reported a lack of effect of maize maturity at harvest on growth rate despite differences in DMI being observed.

No difference in FCE was identified between MS I, MS III, and MS IV, which agrees with the report of Browne et al. (2004), who found no difference in FCE with maize silages of a chemical composition comparable with those in the present study. However, Browne et al. (2004) found an improvement in FCE with maize silage harvested at an earlier stage of maturity (DM: 291 g/kg of fresh weight; starch: 236 g/kg of DM) than occurred in the present experiment.

The ALC-based diet supported increased rates of animal performance, with the BW gains achieved being greater than those predicted using Ministry of Agriculture, Fisheries and Food (1984) values (1,455 vs. 1,201 g/d). Animals offered ALC most likely exhibited compensatory growth, and this is supported by the decreased perinephric plus retroperitoneal fat weights compared with those reported by Keane (2001) and McGee et al. (2006) for comparable animals offered similar diets. This exploitation of compensatory growth coupled with the high energy density of the diet may also have contributed to the greater BW gains than those observed on commercial beef farms (Buckley et al., 1998).

Methane Emissions

Dietary manipulation is one obvious strategy for reducing methane emissions by ruminants. In the present experiment, although methane emissions, expressed in grams per day, were greater than those reported by Nishida et al. (2007) for cattle consuming maize silage, there was no effect of maize maturity at harvest on this index of methane output, and this agrees with the results of Nishida et al. (2007). However, when methane output was expressed relative to DMI, the values were quite similar to those reported by Nishida et al. (2007). The tendency toward a linear decline in methane output relative to DMI that was observed in response to advancing maize maturity at harvest is most likely a function of the observed increase in starch concentration and the simultaneous decline in fiber concentration. Such changes in maize silage chemical composition have been reported to shift rumen fermentation toward propionic acid formation (Sutton et al., 2000), resulting in a decline in the acetate-to-propionate ratio. Propionic acid formation is a net proton-utilization process in the rumen that competes with methanogenesis for H^+, thus providing an alternative H^+ sink to methane production (Hegarty, 1999). Previous research by Johnson et al. (2002) showed an increase in the acetate-to-propionate ratio in rumen fluid as animals were offered maize silage of progressively more advanced maturity. These authors explained that outcome on the basis that starch digestibility decreased with advancing maize maturity at harvest. However, this was not the case in the present experiment, in which starch digestibility showed no evidence of a decline, most likely because of the use of a corn cracker at harvest, facilitating excellent utilization of the maize grain irrespective of the stage of maturity. Furthermore, decreased rumen pH has been associated with increasing dietary starch content, and this has frequently been reported to reduce methane output (Moe and Tyrrell, 1979; Moss et al., 2000). Low rumen pH indirectly reduces methane output by limiting fiber digestion and thus inhibiting the subsequent activity of the methanogenic bacteria (Van Kessel and Russell, 1996). The significantly reduced methane output per kilogram of DMI by cattle offered ALC can also be directly attributed to these factors.

It is generally accepted that as animal productivity increases, methane output per unit of salable animal product will decrease (McCrabb et al., 1998; Lovett et al., 2003). The tendency for decreased methane output per kilogram of carcass gain for maize silages of greater maturity in the present experiment appeared to arise from the slight, although nonsignificant, decrease in methane output per day coupled with the slight, although also nonsignificant, increase in carcass gain, and agrees with that reported by Lovett et al. (2003). The difference observed between the maize silage-based treatments and ALC is more overtly explainable by the reduced methane output and increased carcass gain associated with the ALC diet. Thus, it can be concluded that increasing the nutritional quality of the diet by increasing its starch content reduced methane output per unit of animal product. This can have positive implications for the livestock industry because it provides a pathway for methane mitigation as fewer animal feeding days would be required to produce the same amount of carcass. However, in assessing the overall effects on greenhouse gases, it is important to consider the total direct and indirect greenhouse gases fluxes associated with each option.

It is desirable that strategies for methane mitigation in beef production should not compromise animal performance because this would influence the uptake of such strategies by beef producers. Thus, the high-concentrate diet used in the present experiment promoted high rates of BW and carcass gain coupled with low methane output when compared with the maize silage-based diets. This would allow animals to reach their finishing BW sooner, thereby potentially reducing lifetime emissions through a shorter duration during which

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they emit methane. However, the relatively large rates of BW gain supported by the maize silage-based diets compared with the ALC-based diets together with the tendency for reduced methane output per unit of carcass gain may positively influence the uptake of maize silage feeding regimens. The viability of such feeding regimens may be further strengthened by advances in agronomic practices and plant breeding.

In conclusion, despite no difference being detected in the total output of methane during a 110-d finishing period by cattle consuming diets based on maize silage differing in their stage of maturity at harvest, there was a tendency for a linear reduction in methane output per unit of beef carcass produced as the maturity of maize at harvest advanced. Progressing along the range of starch inputs to feeding concentrates ad libitum markedly reduced methane emissions and increased growth rate compared with the maize silage-based diets. These dietary differences underline different opportunities to decrease enteric methane emissions when cattle are finished over a standard duration or to a standard carcass gain. Thus, they provide an opportunity to reduce the environmental burden of beef production and to reduce the contribution of agriculture to total greenhouse gas emissions. However, to fully interpret the results of this study, a complete life-cycle analysis is required to account for all the on- and off-farm greenhouse gas emissions and sinks involved in producing beef with these contrasting dietary options. This is essential because any potential benefits accruing in terms of reduced methane emissions should not be offset by increases in other greenhouse gases involved in producing or feeding these feedstuffs.

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