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Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content[1]

E. J. Mc Geough,*†[2] P. O'Kiely,*[3] K. J. Hart,† A. P. Moloney,* T. M. Boland,† and D. A. Kenny†

*Teagasc, Grange Beef Research Centre, Dunsany, Co. Meath, Ireland; and †University College Dublin, School of Agriculture, Food Science and Veterinary Medicine, Belfield, Dublin 4, Ireland

ABSTRACT: This study aimed to quantify the methane emissions and feed intake, performance, carcass traits, digestibility, and rumen fermentation characteristics of finishing beef cattle offered diets based on whole-crop wheat (WCW) silages differing in grain content and to rank these relative to diets based on grass silage (GS) and ad libitum concentrates (ALC). In Exp. 1, a total of 90 continental crossbred steers [538 ± 27.6 kg of BW (mean ± SD)] were blocked by BW and assigned in a randomized complete block design to 1 of 6 treatments based on 4 WCW silages [grain-to-straw plus chaff ratios of 11:89 (WCW I), 21:79 (WCW II), 31:69 (WCW III), and 47:53 (WCW IV)], GS, and ALC. Increasing grain content in WCW silage resulted in a quadratic ($P = 0.01$) response in DMI, with a linear ($P < 0.001$) increase in carcass gain [CG; 577 (WCW I), 650 (WCW II), 765 (WCW III), and 757 g/d (WCW IV)]. The G:F also increased linearly ($P < 0.001$) in response to increasing the grain content of WCW silage. A quadratic ($P < 0.01$) response in daily methane output [295 (WCW I), 315 (WCW II), 322 (WCW III), and 273 g/d (WCW IV)], measured using the sulfur hexafluoride tracer technique, was observed in response to increasing the grain content of WCW; however, linear decreases were observed when expressed relative to DMI ($P = 0.01$) and CG ($P < 0.001$). Cattle offered GS exhibited carcass gains similar to those offered WCW silage diets and had greater methane emissions than cattle in any other treatment when expressed relative to DMI. Cattle offered ALC exhibited greater ($P < 0.01$) carcass gains and decreased ($P < 0.001$) methane emissions, irrespective of the unit of expression, compared with cattle in any of the silage-based treatments. In Exp. 2, rumen fermentation parameters were determined using 4 ruminally cannulated Rotbunde-Holstein steers (413 ± 30.1 kg of BW) randomly allocated among WCW I, the average of WCW II and III (WCW II/III), WCW IV, and GS in a 4 × 4 Latin square design. Ruminal pH and total VFA concentration did not differ across dietary treatments. Molar proportion of acetic acid decreased ($P = 0.01$), with propionic acid tending to increase ($P = 0.06$) with increasing grain content. It was concluded that increasing the grain content of WCW silage reduced methane emissions relative to DMI and CG and improved animal performance. However, the relativity of GS to WCW in terms of methane emissions was dependent on the unit of expression used. Cattle offered ALC exhibited decreased methane emissions and greater performance than those offered any of the silage-based treatments.

Key words: cattle, digestibility, methane, performance, sulfur hexafluoride, whole-crop wheat

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INTRODUCTION

In many parts of Northern Europe, grass silage (**GS**) has traditionally been the predominant winter forage for finishing beef cattle. However, its value as a ruminant feedstuff can be challenged because of relatively modest yields of DM in a single harvest and variability in digestibility and ensilability (Mayne and O'Kiely, 2005). Thus, the use of alternative winter forages, such as whole-crop cereals, in beef production systems is of interest. The attractiveness of whole-crop wheat (**WCW**) silage is due to its potential for increased

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[3]Corresponding author: padraig.okiely@teagasc.ie

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yields, increased intake, and ease of preservation compared with GS (Keady, 2005). However, similar to other whole-crop cereal silages, the nutritive value of WCW can vary widely because of factors such as harvest date and cutting height (Kennelly and Weinberg, 2003).

A major environmental issue for beef production systems is the production of enteric methane. Methane is a potent greenhouse gas that arises as a by-product of the fermentation of feed in the gastrointestinal tract of ruminants, globally totaling approximately 80 teragrams annually (Beauchemin et al., 2008). Nutritional manipulation, including increasing the starch content of the diet, has been reported to reduce methane emissions (Moss et al., 2000). Thus, because of the increased starch content of WCW relative to GS, potential benefits may exist for methane abatement by replacing GS with WCW silage and by increasing the grain content in the WCW silage.

To date, no studies have reported the effects of increasing the grain content of WCW silage on enteric methane emissions. This study quantified the methane emissions, feed intake, performance, carcass characteristics, diet digestibility, and rumen fermentation of finishing beef cattle offered diets based on WCW silages differing in grain content, and ranked these data relative to values obtained with standard GS and high-concentrate diets. The hypothesis tested was that increasing the grain content of WCW silage would reduce methane output.

MATERIALS AND METHODS

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

Forage Management, Harvest, Ensilage, and Characterization

Winter wheat (cv. Einstein) was managed using standard agronomic practices (e.g., herbicide, fungicide, growth regulator, and fertilizer) appropriate for high-yielding crops (Conry and Hogan, 2001). At harvest, 300 individual plants (arranged in 6 bundles of 50 plants) were selected at random from the area of crop being harvested and cut to the same stubble height as that achieved by the forage harvester. The grain and straw plus chaff components of each bundle were then separated and weighed. The crop of WCW was harvested without an additive on August 4, 2007, using a precision-chop silage harvester (Claas Jaguar 900 with a 5.2-m-wide direct-cut disc head, Claas, Edmonds, UK) to a mean stubble height of 12 cm. The chopping knife number and feed roller speeds were calculated to give a nominal chop length of 19 mm according to the instructions of the manufacturer. Each trailer-load of WCW was weighed into horizontal, walled, roofed concrete silos (23.0 m long, 4.3 m wide, and 2.3 m high), mechanically compacted (412S JCB, Rocester, Staffordshire, UK), and then sealed beneath 2 layers of black 0.125-mm polythene sheeting (IS 246 1989). Samples from each trailer-load of WCW were stored at −18°C until processing, when they were bowl-chopped (MTK 204 Special, Müller, Saarbrücken, Germany) and composited in chronological groups to produce a total of 6 samples for analysis. The WCW was removed from the silos in December and processed through a combine harvester (Model TX68 Plus, New Holland, Basildon, Essex, UK) to separate grain from straw plus chaff. These 2 components were subsequently reensiled separately in concrete silos and were sealed beneath polythene sheeting as described above for the original WCW. Samples of each component were stored at −18°C until processing, when they were composited to produce a total of 9 samples per silo.

The GS was made from a perennial ryegrass (*Lolium perenne* L.)-dominant sward that was mown on May 22, 2007, using a rotary-disc mower (CatNova 3100T, Pottinger, Grieskirchen, Austria), harvested using a precision-chop harvester (Mex IV, Pottinger), and ensiled, without an additive, in a concrete-wall silo as for the WCW.

Assessment of the aerobic stability of the WCW and GS was carried out using the technique reported by Walsh et al. (2008b). Silage particle size distribution was determined by manual separation according to the technique reported by Mc Geough et al. (2010).

Animal Studies

Exp. 1. This experiment compared the methane output, feed intake, growth rates, apparent digestibility, and plasma urea of steers offered 1 of 6 diets. Dietary treatments WCW I to IV were based on 4 ratios of wheat grain to straw plus chaff (on a DM basis): 11:89 (**WCW I**), 21:79 (**WCW II**), 31:69 (**WCW III**), and 47:53 (**WCW IV**). The appropriate amounts of ensiled grain and straw plus chaff were weighed out of the silos daily and mixed in a feeder wagon (Super-Mix 100, Abbey Farm Machinery, Nenagh, Co. Tipperary, Ireland). A fifth treatment, GS, was used to permit comparison with WCW. All silages were offered ad libitum and were supplemented with 2.60 kg of concentrate DM per animal, offered separately in a single feed daily before offering the allotted silage. The supplemental concentrate was formulated to provide 306 g of CP/kg of DM. A sixth treatment, ad libitum concentrates (**ALC**) supplemented with 1.28 kg of GS DM per animal daily, was used as a positive control. Both the supplemental and ad libitum concentrates were in pelleted form.

Animals were acquired from commercial beef farms and offered GS for ad libitum consumption for 70 d before the experimental period. All animals were treated for internal and external parasites (Dectomax Pour-on, Pfizer Animal Health, St. Louis, MO) and were vac-

cinated against infectious bovine rhinotracheitis and parainfluenza (Bovilis, Intervet/Schering-Plough Animal Health, Boxmeer, the Netherlands) before the experiment. Ninety continental crossbred steers (predominantly Charolais and Limousin), with a mean initial BW of 538 kg (SD 27.6 kg), were selected and weighed, unfasted, at 0800 h 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 15 replicate blocks on a descending BW basis and were randomly allocated to 1 of the 6 dietary treatments, giving 15 steers per treatment. Animals were grouped in 3 pens per treatment, with 5 animals per pen (lying area = 2.52 m^2/animal) in a slatted-floor building, with pens within treatment equally distributed throughout the building. Animals were individually offered their respective diets through electronically controlled Calan doors (American Calan Inc., Northwood, NH) in a single feed daily. All animals had continuous access to clean, fresh water for the duration of the study. Refused feed was recorded daily for each animal and discarded twice weekly, with ad libitum access being based on approximately 1.1 times the intake of the previous day. Diets were offered for 154 d, after which final BW was recorded and animals were immediately slaughtered at a commercial abattoir.

Daily BW gain was calculated by deducting the initial BW from the final BW and dividing it by the number of days in the experimental period. A carcass yield of 510 g of carcass/kg of BW was assumed to estimate initial carcass weight (Caplis et al., 2005). Carcass yield at the end of the experiment was determined by dividing the cold carcass weight by final BW. Carcass fat and conformation scores were determined using a video-imaging analysis system (VCS 2000, E + V, Oranienburg, Germany) based on the European carcass classification scale (EUROP), as described by the Commission of the European Communities (1982). Perinephric and retroperitoneal fat was removed from both sides of the carcass and weighed. The G:F was expressed as kilograms of carcass gain per 1,000 kg of DMI. All silages were sampled 3 times weekly (Monday, Wednesday, and Friday) and stored at −18°C until composited in units of 3 wk, whereas concentrates were sampled once per week, stored at −18°C, and also composited every 3 wk.

Methane emissions were determined using the sulfur hexafluoride (**SF_6**) tracer technique (Johnson et al., 1994), with each animal sampled daily over 5 consecutive days, in one period during the experiment. There were 5 methane sampling periods during this study, with 3 different animals from each treatment sampled during each period. Thus, animals from blocks 1 to 3, 4 to 6, 7 to 9, 10 to 12, and 13 to 15 were sampled on d 41 to 45, d 62 to 66, d 90 to 94, d 111 to 115, and d 132 to 136, respectively. Methane sampling was carried out in a separate housing facility, with animals tethered 10 d before the commencement of sampling while remaining on their individual diets. Tethering occurred 10 d before sampling to allow animals to become acclimated after their temporary move to the sampling facility. Brass permeation tubes filled with SF_6, and with known release rates of 3.14 mg/d (SD 0.88 mg/d), were administered orally to each of the 18 animals 10 d before methane sampling to allow the tracer gas to equilibrate in the rumen. Animals were fitted with gas collection halters connected to preevacuated polyvinyl chloride canisters designed to fill halfway over 24 h, with sampling commencing at 0700 h daily. The collection canister was located above each animal to reduce the risk of equipment damage and was connected to the halter by using peak tubing inside airline flexible-coil tubing. After gas collection, the pressure readings were recorded and the canisters were pressurized to 1,250 hPa using pure N_2. Samples of the ambient air in the sampling facility were also obtained to determine the background concentrations of methane and SF_6, with these values then subtracted from the animal values to get the net output in the expired breath.

Methane emissions (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 its daily GE and DM intakes (during methane sampling) and daily carcass gain (throughout the entire experimental period), respectively. On completion of the methane sampling period, the animals returned to their respective pens in the slatted-floor building.

Blood samples were collected on the final day of each methane sampling period from each of the animals assigned to sampling. Samples were obtained via jugular venipuncture into evacuated 10-mL vials (Greiner Vacuette, Cruinn Diagnostics, Dublin, Ireland) containing lithium heparin, immediately before feeding (0830 h) and 2 and 6 h after feeding, with the mean plasma urea value for each animal used for statistical analysis.

Diet digestibility coefficients were determined for all animals by using the indigestible AIA marker technique, as described by Van Keulen and Young (1977). There were 5 in vivo digestibility measurement periods, with 3 animals from each treatment sampled during each period. Animals from blocks 1 to 3, 4 to 6, 7 to 9, 10 to 12, and 13 to 15 were sampled on d 47 to 51, 68 to 72, 96 to 100, 117 to 121, and 138 to 142, respectively. Representative samples of each of the offered feedstuffs were obtained daily, in duplicate, and composited at the end of the 5-d sampling period, with samples of refused feeds obtained daily and pooled per animal at the end of the sampling period. Fecal grab samples (200 g) were obtained from each animal daily for 5 d, via rectal palpation at 0800 h before feeding, and pooled individually at the end of the sampling period.

Exp. 2. This experiment determined the rumen fermentation variables of steers offered 1 of 4 dietary treatments, of which 3 were based on WCW silages. This experiment was contemporaneous with Exp. 1. The 3 WCW silages had grain-to-straw plus chaff ratios of 11:89 (WCW I), 26:74 [average of WCW II and III (**WCW II/III**)], and 47:53 (WCW IV), with a fourth

forage treatment, GS, also offered. Four ruminally cannulated Rotbunde-Holstein, with a mean initial BW of 413 kg (SD 30.1 kg), were randomly allocated to 1 of the 4 dietary treatments in a 4 × 4 Latin square design. Each period within the Latin square consisted of 20 d of dietary adaptation followed by 2 d of sampling. Animals were offered their respective diets in a single feed at 1030 h daily, with all silages offered ad libitum plus 2.60 kg of concentrate DM for 18 d, after which silage intake was restricted to 0.90 of average silage intake for the final 2 d of adaptation. The supplemental concentrate, as used in Exp. 1, was offered to animals at 2.60 kg of DM in a single feed daily for 18 d, and then at a concentrate-to-silage ratio equivalent to the mean of the animals on the corresponding treatment during the preceding week in Exp. 1. This was followed by 2 d of rumen sampling. Samples of the offered silages and supplemental concentrate obtained on d 19 and 20 were combined and the process was repeated for d 21 and 22, to give 2 samples of each feed component per period. These were stored at −18°C until processing and analysis. Rumen fluid samples of approximately 200 mL were collected through the rumen cannula from each animal before feeding (0900 h) and at 2, 6, and 12 h after feeding, with pH measured immediately and a 20-mL subsample preserved with 0.5 mL of 9 *M* sulfuric acid. Rumen samples were centrifuged at 10,000 × *g* for 15 min at 4°C and then stored at −18°C until subsequent analysis. Processing and chemical analysis of all feed, fecal, gas, blood, and rumen fluid samples were carried out as described by Mc Geough et al. (2010).

Statistical Analysis

Exp. 1. Three animals were removed from the study (1 animal each from the WCWII, WCWIII, and GS treatments) for reasons unrelated to dietary treatment, resulting in data from 87 animals being analyzed. Normality of distribution and homogeneity of variance were analyzed using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC). All data were subjected to ANOVA using the MIXED procedure, with the model including terms for treatment (df = 5) and block (df = 14). Within WCW treatments, linear and quadratic contrasts were carried out using contrast statements in SAS to determine the effects of increasing grain content on the traits of interest. Contrast statements were used to determine the differences between the mean of the WCW treatments and GS and also between the mean of the silage-based treatments and ALC. 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 dietary treatment, 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 following 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. Treatment effects were declared significant at $P < 0.05$.

Data pertaining to AIA digestibility that were not normally distributed were transformed by raising the variable to the power of lambda because transformations using the natural logarithm were inadequate. The appropriate lambda value was obtained by conducting a Box-Cox transformation analysis in the TRANSREG procedure of SAS. Thus, lambda was −1.75 for DM digestibility, 3.00 for starch, −0.75 for NDF, and −1.25 for CP. The transformed data were used for statistical analysis; however, the corresponding least squares means and SE of the nontransformed data are presented to facilitate interpretation of the results. Data pertaining to methane emissions (g/d) were not normally distributed and were transformed using the natural logarithm, with results presented as described for the AIA digestibility data.

Exp. 2. Values for rumen variables were averaged for each time point for the 2 d of sampling, with the mean of the 4 time point values determined for each animal. Data were checked for normality and homogeneity of variance as described previously. Data pertaining to the proportion of D-lactic acid of the total lactic acid was found not to be normally distributed and was transformed using the natural logarithm, with the results presented as described previously. Data were analyzed using the MIXED procedure of SAS for a 4 × 4 Latin square. Data were analyzed according to the following statistical model: $Y_{ijk} = \mu + D_i + B_j + P_k + e_{ijk}$, where μ, D_i, B_j, and P_k are as described previously, and e_{ijk} is the associated error. Linear and quadratic contrasts were carried out to determine the effect of increasing the grain content of WCW silage on the variables of interest. Contrast statements were used to determine differences between the mean of the WCW treatments and GS for traits of interest.

RESULTS

Silage and Concentrate Characteristics

The mean chemical composition of the preensiled wheat plant components and harvested whole crop are presented in Table 1. Increasing the grain content of WCW silage numerically increased the DM and starch concentrations and the IVDMD, with concomitant numerical decreases in NDF and ADF concentrations and buffering capacity (Table 2). The content of CP did not differ markedly with increasing WCW silage grain content. Grass silage IVDMD, CP, buffering capacity, ash, ME, and GE values were numerically greater than for any of the WCW silages. In addition, the proportion of silage particles ≤25 mm increased with increasing grain content, whereas GS had a greater proportion of particles in the larger size categories. The mean chemical composition of the concentrates is presented in Table 3. All the WCW silages were potentially unstable on exposure to air, with the time taken for the tempera-

Table 1. Chemical composition of the whole-crop and plant components of wheat before ensiling (mean ± SD)

Item	Plant component			
	Grain	Straw	Chaff	Whole-crop
DM, g/kg	739 ± 90.3	457 ± 68.1	656 ± 34.5	471 ± 19.5
Chemical composition of DM, g/kg of DM unless otherwise stated				
IVDMD, g/kg	799 ± 25.3	490 ± 16.5	338 ± 58.0	603 ± 16.8
CP	133 ± 2.7	64 ± 11.9	89 ± 7.9	90 ± 4.0
Starch	694 ± 57.4	ND[1]	ND	508 ± 24.0
Ash	17 ± 3.0	61 ± 5.3	55 ± 9.2	47 ± 15.5

[1]ND = not determined.

ture to increase more than 2°C above ambient being 36, 29, 25, and 27 h for WCW I to IV, respectively, with the accumulated temperature increase to 120 h being 67, 85, 80, and 81°C, respectively. The corresponding values for GS were 91 h and 16°C. The mean chemical composition of each of the experimental diets is presented in Table 4.

Exp. 1

Feed and Energy Intake. Increasing the grain content of WCW silage resulted in a quadratic ($P = 0.01$) increase in both silage and total DMI (Table 5). Intake of GE was not affected (linear, $P = 0.98$; quadratic, $P = 0.20$) by increasing the grain content of WCW silage; however, a linear ($P < 0.001$) increase in ME intake was observed. Linear ($P = 0.004$) and quadratic responses ($P = 0.04$) in CP intake were observed on increasing the grain content of WCW silage. Cattle offered WCW had greater ($P < 0.001$) DM, GE, and ME intakes than those offered GS; however, no difference ($P = 0.78$) in CP intake was observed. Cattle offered ALC exhibited DM, GE, and CP intakes that did not differ ($P = 0.12$) from those offered the silage-based treatments, but they had greater intakes of GE and ME ($P < 0.001$).

Animal Performance, G:F, Carcass Characteristics, and Plasma Urea. Increasing the grain content of WCW silage resulted in a linear ($P = 0.01$) and quadratic ($P = 0.03$) response in final BW and daily BW gain (Table 5). Linear increases in carcass yield ($P = 0.01$), carcass weight ($P < 0.001$), and rate of carcass gain ($P < 0.001$) were also observed in response to increasing the grain content of WCW silage. No linear or quadratic responses (linear, $P = 0.94$; quadratic, $P = 0.12$) in carcass conformation and fat scores were identified. Increasing the grain content of WCW silage resulted in a quadratic ($P = 0.01$) response in perinephric plus retroperitoneal fat weight. A linear improvement in G:F was observed when the grain content of WCW silage was altered. Plasma urea concentration was not affected (linear, $P = 0.69$; quadratic, $P = 0.86$) by increasing the grain content of WCW silage.

Cattle offered WCW exhibited final BW, BW gain, carcass yield, carcass weight, and carcass gain that did not differ ($P = 0.30$) from those offered GS. Similarly no differences ($P = 0.27$) were observed between WCW and GS for carcass conformation or fat scores or for perinephric plus retroperitoneal fat weight. However, cattle offered GS were more ($P = 0.003$) efficient at converting feed into carcass than those offered WCW.

Cattle offered ALC exhibited greater ($P < 0.001$) daily BW gain, final BW, rate of carcass gain, and carcass weight than those on any of the silage-based treatments. Carcass yield, conformation and fat scores, and plasma urea did not differ from cattle on the silage-based treatments. Perinephric plus retroperitoneal fat weight for cattle offered ALC was greater ($P = 0.002$) than that for cattle on the silage-based treatments, with cattle offered ALC having a greater G:F ($P < 0.01$) than those offered silage-based diets.

In Vivo Apparent Diet Digestibility. In this section, the comments relate to the statistical findings obtained using the transformed values, with the exception of DMI and starch plus NDF digestibility. Increasing the grain content of WCW silage resulted in a quadratic ($P < 0.001$) increase in total DMI (Table 6) and a linear ($P < 0.001$) increase in apparent in vivo DM digestibility. Linear ($P = 0.01$) and quadratic ($P = 0.02$) responses in starch digestibility were observed on increasing the grain content of WCW silage, with a quadratic response ($P < 0.01$) in NDF digestibility also observed.

Cattle offered GS exhibited greater ($P < 0.001$) DM, NDF, and CP digestibilities than those offered WCW silage. Cattle offered ALC had greater ($P < 0.001$) DM, starch, and CP digestibilities than those consuming the silage-based treatments. However, no differences ($P = 0.70$) in NDF digestibility were observed.

Methane Emissions. Comments pertaining to methane output per day relate to the statistical findings obtained using the transformed values. Increasing the grain content of WCW silage resulted in a quadratic ($P < 0.01$) response in total daily methane emissions (Table 7). Increasing the grain content of WCW silage resulted in a linear ($P = 0.01$) decrease in methane emissions when expressed relative to DMI, with no linear or quadratic responses (linear, $P = 0.11$; quadratic, $P = 0.21$) in methane emitted proportional to GE intake observed. Increasing the grain content of WCW silage resulted in a linear ($P < 0.001$) reduction in methane output per kilogram of carcass gain.

Total daily methane emission for cattle offered WCW did not differ ($P = 0.70$) from that of cattle offered GS;

Table 2. Chemical composition and particle length of whole-crop wheat (WCW)[1] and grass silages (GS) at feeding (mean ± SD; Exp. 1)

	WCW silage				
Item	I	II	III	IV	GS
DM,[2] g/kg	462 ± 13.2	498 ± 15.9	546 ± 13.6	584 ± 12.5	256 ± 16.7
Composition of DM, g/kg of DM unless otherwise stated					
IVDMD, g/kg	619 ± 22.0	659 ± 16.9	706 ± 17.6	760 ± 26.9	793 ± 28.5
Ash	55 ± 3.1	49 ± 2.2	47 ± 4.4	38 ± 2.7	103 ± 14.8
AIA[3]	19.3 ± 1.23	15.1 ± 1.16	12.9 ± 1.29	10.3 ± 1.60	7.2 ± 1.38
Starch	155 ± 22.2	268 ± 26.1	353 ± 26.1	436 ± 31.6	ND[4]
CP	104 ± 2.8	106 ± 2.6	109 ± 2.4	113 ± 2.6	140 ± 10.8
NDF	524 ± 25.5	444 ± 15.2	379 ± 19.5	310 ± 28.8	513 ± 17.4
ADF	310 ± 12.3	258 ± 10.6	210 ± 14.4	163 ± 9.8	311 ± 12.8
WSC[5]	9.3 ± 2.71	13.2 ± 3.21	18.1 ± 4.51	22.7 ± 5.15	8.0 ± 0.52
BC,[6] mEq/kg of DM	468 ± 52.9	405 ± 39.6	360 ± 36.0	307 ± 38.6	1,016 ± 56.2
GE, MJ/kg of DM	18.7 ± 0.86	17.7 ± 0.69	17.6 ± 0.51	17.9 ± 0.55	19.9 ± 1.36
ME,[7] MJ/kg of DM	9.0 ± 0.34	9.7 ± 0.27	10.5 ± 0.30	11.5 ± 0.46	11.3 ± 0.38
Fermentation characteristics, g/kg of DM unless otherwise stated, except pH					
pH	3.97 ± 0.215	4.05 ± 0.218	4.14 ± 0.208	4.22 ± 0.190	3.93 ± 0.120
Ethanol	11.9 ± 2.52	7.8 ± 0.89	5.1 ± 1.33	5.4 ± 1.33	17.4 ± 3.51
Acetic acid	13.9 ± 2.03	10.7 ± 1.14	8.2 ± 1.38	7.4 ± 0.77	28.5 ± 13.28
Propionic acid	ND	0.2 ± 0.30	0.5 ± 0.38	1.0 ± 0.37	4.5 ± 2.61
Butyric acid	ND	ND	ND	ND	9.2 ± 3.50
D-Lactic acid + L-lactic acid	34 ± 14.2	33 ± 10.0	28 ± 9.7	24 ± 4.7	103 ± 12.1
FP[8]	59 ± 16.4	51 ± 10.4	42 ± 9.8	38 ± 5.8	160 ± 16.3
D-Lactic acid[9]	0.49 ± 0.003	0.51 ± 0.002	0.50 ± 0.003	0.50 ± 0.002	0.50 ± 0.001
Lactic acid:total FP	0.55 ± 0.116	0.62 ± 0.084	0.65 ± 0.099	0.63 ± 0.033	0.65 ± 0.070
NH_3-N, g/kg of total N	59 ± 14.7	57 ± 13.4	48 ± 9.0	44 ± 7.7	76 ± 6.1
Particle length, g of DM/kg of DM					
0 to 25 mm	789 ± 49.3	853 ± 35.7	884 ± 1.24	897 ± 32.8	176 ± 10.2
26 to 50 mm	111 ± 19.5	99 ± 13.0	81 ± 2.9	55 ± 18.0	258 ± 9.1
51 to 75 mm	74 ± 62.1	28 ± 12.7	21 ± 2.7	29 ± 2.4	207 ± 2.1
76 to 100 mm	15 ± 10.3	16 ± 11.9	7 ± 2.2	8 ± 3.5	169 ± 5.5
>100 mm	11 ± 7.0	4 ± 1.5	7 ± 2.5	12 ± 18.0	189 ± 2.3

[1]Grain to straw plus chaff: I = 11:89; II = 21:79; III = 31:69; IV = 47:53.
[2]Corrected for loss of volatiles during oven drying.
[3]Based only on samples obtained during in vivo digestibility determination.
[4]ND = not determined.
[5]Water-soluble carbohydrates.
[6]Buffering capacity.
[7]Estimated based on in vitro digestible OM in total DM (AFRC, 1993).
[8]Fermentation products (acetic acid, propionic acid, butyric acid, ethanol, and lactic acid).
[9]D-Lactic acid as a proportion of total lactic acid.

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

Item	ALC concentrate	WCW concentrate
Ingredient, g/kg		
Rolled barley	820	460
Soybean (dehulled, solvent extracted)	100	460
Sugarcane molasses	50	50
Mineral and vitamin premix[2]	20	20
Vegetable oil	10	10
Chemical composition, g/kg of DM unless otherwise stated		
DM, g/kg	863 ± 4.3	868 ± 3.6
IVDMD, g/kg	872 ± 11.4	891 ± 5.2
CP	161 ± 6.7	302 ± 13.4
Ash	53 ± 4.8	72 ± 2.8
AIA[3]	3.7 ± 1.01	2.2 ± 0.43
Starch	505 ± 34.8	252 ± 29.0
NDF	160 ± 10.2	134 ± 5.8
ADF	55 ± 6.4	66 ± 7.6
GE, MJ/kg of DM	19.7 ± 0.11	19.3 ± 0.23
ME,[4] MJ/kg of DM	12.9 ± 0.21	12.9 ± 0.09

[1]ALC = ad libitum concentrates; WCW = whole-crop wheat.
[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 selenium as sodium selenite; 10 mg of copper as cupric sulfate; 10 mg of copper as cupric chelate of AA hydrate.
[3]Based only on samples obtained during in vivo digestibility determination.
[4]Estimated using Eq. [142] in Energy and Protein Requirements of Ruminants (AFRC, 1993).

however, methane emission relative to DMI was less ($P < 0.001$) for cattle offered WCW than for those offered GS. Methane emission proportional to GE intake was less ($P = 0.02$) for cattle offered WCW than for those offered GS, with no difference ($P = 0.65$) between these treatments for methane emission relative to carcass gain. Cattle offered ALC exhibited decreased ($P < 0.001$) methane emission compared with those consuming the silage-based treatments irrespective of the unit of expression.

Exp. 2: Silage and Concentrate Composition, and Rumen Fermentation Variables

The chemical composition values (data not shown) of the WCW silages, GS, and supplemental concentrate used in this study were similar to those reported in Exp. 1. Increasing the grain content of WCW silage did not affect (linear, $P = 0.49$; quadratic, $P = 0.24$) ruminal pH or D-lactic acid concentration; however, a linear ($P < 0.01$) increase in L-lactic acid concentration was identified (Table 8). Increasing the grain content of WCW silage resulted in a linear ($P = 0.01$) decrease in ruminal NH_3 concentration, whereas total VFA concentration was not affected ($P = 0.62$) by dietary treatment. However, increasing the grain content of WCW silage resulted in a linear decrease ($P = 0.01$) in the molar proportion of acetic acid, with a simultaneous linear increase ($P = 0.01$) in propionic acid proportion. The ratios of acetate to propionate and of lipogenic to glucogenic VFA, defined as the nonglucogenic ratio, decreased linearly ($P = 0.01$) with increasing WCW silage grain content.

Table 4. Chemical composition of the whole-crop wheat (WCW) silage,[1] grass silage (GS),[2] and ad libitum concentrate (ALC)[3] diets

Composition of the diet, g/kg of DM unless otherwise stated	WCW silage				GS	ALC
	I	II	III	IV		
NDF	428	373	323	268	406	203
ADF	250	214	177	140	242	86
Starch	179	264	330	392	71	444
CP	153	151	154	158	186	158
Ash	59	54	53	46	94	59
GE, MJ/kg of DM	18.9	18.1	18.0	18.2	19.7	19.7
ME, MJ/kg of DM	10.0	10.4	11.1	11.8	11.8	12.7

[1]WCW silage plus 2.60 kg of concentrate DM. Grain to straw plus chaff: I = 11:89; II = 21:79; III = 31:69; IV = 47:53.
[2]GS plus 2.60 kg of supplemental concentrate DM.
[3]ALC plus 1.28 kg of GS DM.

Table 5. Feed intake, performance, carcass traits, feed conversion efficiency, and plasma urea concentration of steers offered the whole-crop wheat (WCW) silage,[1] grass silage (GS),[2] and ad libitum concentrate (ALC)[3] diets (Exp. 1)

	WCW silage							*P*-value			
Item	I	II	III	IV	GS	ALC	SEM[4]	Linear[5]	Quadratic[5]	WCW vs. GS[6]	ALC vs. silage[7]
Feed intake											
Silage intake, kg of DM/d	7.97	8.81	8.78	8.38	6.59	1.31	0.206	0.21	0.004	<0.001	<0.001
Total DMI, kg/d	10.57	11.41	11.38	10.98	9.20	10.86	0.219	0.23	0.01	<0.001	0.54
Total DMI:BW, g/kg	17.54	18.44	18.22	17.72	15.05	16.95	0.268	0.79	0.01	<0.001	0.14
GE intake, MJ/d	200	207	205	201	183	211	4.0	0.98	0.20	<0.001	0.12
ME intake, MJ/d	105	119	126	129	108	138	2.4	<0.001	0.04	<0.001	<0.001
CP intake, kg/d	1.62	1.72	1.74	1.73	1.71	1.72	0.027	0.004	0.04	0.78	0.56
Performance, feed conversion efficiency, and plasma urea											
Initial BW, kg	539	539	538	538	539	537	0.8	0.56	0.69	0.54	0.25
Final BW, kg	665	700	708	700	682	744	9.8	0.01	0.03	0.35	<0.001
BW gain, g/d	820	1,046	1,103	1,043	929	1,335	62.5	0.01	0.03	0.31	<0.001
Carcass yield,[8] g/kg	540	529	548	553	546	552	4.8	0.01	0.12	0.51	0.12
Carcass wt, kg	359	370	387	386	372	410	5.3	<0.001	0.27	0.59	<0.001
Carcass gain, g/d	577	650	765	757	664	915	34.0	<0.001	0.26	0.55	<0.001
Conformation score[9]	2.93	2.87	3.23	2.80	2.93	3.27	0.117	0.94	0.12	0.82	0.06
Fat score[10]	3.00	3.36	3.28	3.13	3.18	3.47	0.128	0.57	0.06	0.94	0.13
PRF,[11] kg	8.83	10.90	11.94	9.89	9.49	13.86	0.693	0.18	0.01	0.27	<0.001
PRF, g/kg carcass	24.5	29.4	30.7	25.5	25.5	34.1	1.87	0.61	0.01	0.56	0.002
G:F[12]	55.0	57.3	67.3	68.9	72.1	84.2	2.76	<0.001	0.83	0.003	<0.001
BW gain:ME intake, g/MJ	7.75	9.18	8.70	8.02	8.51	9.66	0.402	0.86	0.01	0.84	0.01
Carcass gain:ME intake, g/MJ	5.53	5.70	6.13	5.85	6.13	6.64	0.235	0.20	0.36	0.24	0.004
Plasma urea, mmol/L	5.4	5.6	5.2	5.4	4.4	5.6	0.22	0.69	0.86	<0.001	0.12

[1]WCW plus 2.60 kg of supplemental concentrate DM. Grain to straw plus chaff: I = 11:89; II = 21:79; III = 31:69; IV = 47:53.
[2]GS plus 2.60 kg of supplemental concentrate DM.
[3]ALC plus 1.28 kg of GS DM.
[4]SEM for the 6 dietary treatments, with n = 15 steers/treatment.
[5]Linear and quadratic effects of increasing the grain content of WCW silage.
[6]The mean of the WCW-based treatments vs. the GS-based treatment.
[7]ALC treatment vs. the mean of the silage-based treatments.
[8]Cold carcass weight:final BW.
[9]Eurpean Union Beef Carcass Classification Scheme: scale 1 (poorest = P) to 5 (best = E).
[10]Eurpean Union Beef Carcass Classification Scheme: scale 1 (fattest) to 5 (leanest).
[11]Perinephric plus retroperitoneal fat.
[12]Kilograms of carcass gain/1,000 kg of DMI.

Table 6. In vivo apparent digestibility of whole-crop wheat (WCW) silage,[1] grass silage (GS),[2] and ad libitum concentrate (ALC)[3] diets (Exp. 1)

	WCW silage							*P*-value			
Item	I	II	III	IV	GS	ALC	SEM[4]	Linear[5]	Quadratic[5]	WCW vs. GS[6]	ALC vs. silage[7]
Total DMI, kg/d	10.3	11.6	12.0	10.7	8.9	10.4	0.30	0.24	<0.001	<0.001	0.36
Starch intake, kg/d	1.98	3.19	3.80	4.14	0.63	4.43	0.123	<0.001	0.001	<0.001	<0.001
NDF intake, kg/d	4.37	4.55	4.12	2.98	3.64	2.05	0.126	<0.001	<0.001	0.02	<0.001
CP intake, kg/d	1.53	1.70	1.76	1.65	1.62	1.66	0.036	0.01	0.001	0.33	0.25
In vivo apparent digestibility[8]											
DM	0.60	0.65	0.67	0.70	0.83	0.78	0.010	<0.001	0.50	<0.001	<0.001
Starch	0.98	0.99	0.99	0.99	NA	0.99	0.001	0.01	0.02	NA	<0.001
NDF	0.36	0.40	0.40	0.35	0.82	0.47	0.016	0.13	0.002	<0.001	0.70
CP	0.62	0.63	0.60	0.64	0.79	0.70	0.012	0.97	0.11	<0.001	<0.001

[1]WCW silage plus 2.60 kg of supplemental concentrate DM. Grain to straw plus chaff: I = 11:89; II = 21:79; III = 31:69; IV = 47:53.
[2]GS plus 2.60 kg of supplemental concentrate DM.
[3]ALC plus 1.28 kg of GS DM.
[4]SEM for the 6 dietary treatments, with n = 15 steers/treatment.
[5]Linear and quadratic effects of increasing the grain content of WCW silage.
[6]The mean of the WCW-based treatments vs. the GS-based treatment.
[7]ALC treatment vs. the mean of the silage-based treatments.
[8]Untransformed means and SEM presented for clarity. *P*-values are based on transformed data.

Table 7. Methane emissions from finishing beef cattle offered whole-crop wheat (WCW) silage,[1] grass silage (GS),[2] and ad libitum concentrate (ALC)[3] diets (Exp. 1)

	WCW silage							*P*-value			
Item	I	II	III	IV	GS	ALC	SEM[4]	Linear[5]	Quadratic[5]	WCW vs. GS[6]	ALC vs. silage[7]
CH_4,[8] g/d	295	315	322	273	312	180	9.1	0.11	0.004	0.70	<0.001
CH_4, g/kg of DMI	30.1	27.5	28.0	25.9	35.6	15.3	0.85	0.01	0.80	<0.001	<0.001
CH_4, % GE intake	8.90	8.24	8.52	6.79	9.72	3.71	0.277	0.11	0.21	0.02	<0.001
CH_4, g/kg of carcass gain	534	432	412	325	443	182	28.5	<0.001	0.82	0.65	<0.001

[1]WCW silage plus 2.60 kg of supplemental concentrate DM. Grain to straw plus chaff: I = 11:89; II = 21:79; III = 31:69; IV = 47:53.
[2]GS plus 2.60 kg of supplemental concentrate DM.
[3]ALC plus 1.28 kg of GS DM.
[4]SEM for the 6 dietary treatments, with n = 15 steers/treatment.
[5]Linear and quadratic effects of increasing the grain content of WCW silage.
[6]The mean of the WCW-based treatments vs. the GS-based treatment.
[7]ALC treatment vs. the mean of the silage-based treatments.
[8]Untransformed means and SEM presented for clarity. *P*-values are based on transformed data.

Table 8. Feed intake and rumen fermentation variables of steers offered the whole-crop wheat (WCW) silage[1] and grass silage (GS)[2] diets (Exp. 2)

	WCW silage					*P*-value		
Item	I	II/III	IV	GS	SEM[3]	Linear[4]	Quadratic[4]	WCW vs. GS[5]
Feed intake								
Silage DMI, kg/d	6.39	7.66	9.57	5.85	0.327	<0.001	0.45	0.002
Total DMI, kg/d	8.54	9.99	12.47	8.38	0.497	0.001	0.43	0.01
Rumen fermentation variable								
pH	6.60	6.37	6.48	6.72	0.111	0.49	0.24	0.11
D-Lactic acid, mmol/L	0.17	0.18	0.18	0.19	0.013	0.59	0.93	0.55
L-Lactic acid, mmol/L	0.11	0.17	0.18	0.21	0.011	0.01	0.06	0.004
Proportion of D-lactic[6]	61.7	50.5	51.2	46.7	1.131	<0.001	0.01	<0.001
NH_3, mmol/L	8.73	6.54	4.20	4.31	0.873	0.01	0.94	0.07
Total VFA, mmol	86	90	83	88	8.7	0.85	0.62	0.89
Molar proportion, mmol/mol of VFA								
Acetic acid	673	639	576	595	12.1	0.01	0.40	0.06
Propionic acid	151	189	238	246	12.0	0.01	0.77	0.01
Butyric acid	143	141	138	126	8.5	0.71	0.97	0.19
Valeric acid	33	30	48	33	2.6	0.02	0.03	0.22
Acetate:propionate	4.5	3.5	2.4	2.5	0.27	0.01	0.91	0.03
NGR[7]	6.5	5.0	3.5	3.6	0.41	0.01	0.95	0.03

[1]WCW silage plus 2.60 kg of supplemental concentrate DM. Grain to straw plus chaff: I = 11:89; II/III = 26:74; IV = 47:53.
[2]GS plus 2.60 kg of supplemental concentrate DM.
[3]SEM for the 4 dietary treatments, with n = 12 steers/treatment.
[4]Linear and quadratic effects of increasing the grain content of WCW silage.
[5]The mean of the WCW-based diets vs. the GS-based treatment.
[6]D-Lactic acid as a proportion of total lactic acid. Untransformed means and SEM presented for clarity. *P*-values are based on transformed data.
[7]Nonglucogenic ratio = acetic acid + (2 × butyric acid)/propionic acid.

No differences ($P = 0.07$) in ruminal pH, D-lactic acid, NH_3, or total VFA were identified between WCW and GS. Cattle offered GS exhibited a greater molar proportion of propionic acid ($P = 0.01$), ratio of acetate to propionate ($P = 0.03$), and nonglucogenic ratio ($P = 0.03$) than those offered GS; however, no differences ($P = 0.06$) were observed in the molar proportions of acetic, butyric, or valeric acids.

DISCUSSION

Silage Characteristics

Harvesting an immature crop of wheat with a forage harvester typically used for direct-cut precision-chop harvesting of whole-crop cereal and subsequently separating the resulting silage into a predominantly grain component and a predominantly straw plus chaff component was considered necessary to simulate offering cattle a series of WCW silages differing in grain content. Using a combine harvester to harvest the crop would not have resulted in grain breakage and straw shortening comparable with those of conventional whole-crop cereal, although it would have allowed immediate separation of the plant components. Additionally, fermentation of the whole crop rather than of the grain and straw plus chaff separately was desirable because it was possible that either component might have fermented differently if ensiled separately than if ensiled together, with possible implications for feed chemical composition and subsequent animal measurements.

The 4 ratios of WCW silage grain to straw plus chaff were chosen to represent the likely spectrum of WCW starch contents found on commercial farms. The WCW silages were well preserved, as evidenced by their fermentation product profile, thus indicating that the processes involved in their production were performed satisfactorily. The observed trends in WCW silage chemical composition as grain content increased are in agreement with those of Walsh et al. (2009), who examined the effect of increasing the grain content of baled WCW and barley silages. The GS used was of good quality, as evidenced by the significantly greater IVDMD (793 vs. 676 g/kg) compared with GS typically produced on Irish farms (Keating and O'Kiely, 1997). As expected, the chemical and physical composition of those parts of the whole-crop cereal and GS used in Exp. 2 (data not presented) were similar to the composition of those used throughout Exp. 1.

Feed and Energy Intake

One of the perceived benefits of replacing GS with WCW silage in commercial feeding regimens is the opportunity to increase silage intake. In this study, intakes of WCW silage (kg/d) were greater than in previous reports (O'Kiely and Moloney, 1995; Walsh et al., 2008a,b) and may be partially due to the generally

greater digestibility of the WCW silage in the present study. The WCW silage DMI in the present study was also greater than reported by Walsh et al. (2009). However, when expressed relative to BW, the values recorded by Walsh et al. (2009) were greater than those in this study, possibly because of the decreased dietary NDF digestibility observed in the current study. Whereas Walsh et al. (2009) demonstrated a linear increase in DMI with increasing WCW silage grain content, the quadratic effect in Exp. 1 reflects a deviation in the intake response with WCW IV. This deviation may be a consequence of the animal being able to maintain increased ME intake by consuming a smaller quantity of feed of greater ME concentration. Although increasing the grain content of WCW silage resulted in a quadratic response in DMI, a linear increase in ME intake was observed, with this response most likely facilitated by the increasing starch content offsetting the effect of the reduced DMI of WCW IV. Similarly, a progressive increase in energy intake has been reported by Patterson et al. (2000) for an increasing quantity of grain in GS diets.

The inclusion of GS in this study permits comparison of WCW silages with the forage-based diet most commonly offered to finishing beef cattle in Ireland. Grass silage and total DMI of this treatment were significantly less than for the WCW treatments, which is perhaps surprising given the greater digestibility of GS. This response may be related to several factors. First, the longer mean particle size of GS compared with WCW silages may have slowed passage rate from the rumen (Galyean and Owens, 1991; Allen, 1996), thus reducing silage intake. Second, the more extensive fermentation of GS during ensiling, as evidenced by their greater concentration of fermentation products, may also have limited intake (Huhtanen et al., 2007). Subsequently, the reduced ME intake observed with GS compared with the other treatments can be attributed to the decreased DMI of this diet more than offsetting its apparently greater ME content.

Cattle offered ALC exhibited typical DMI for animals of comparable type and size (McGee et al., 2006). However, despite the similar DMI observed between ALC and the silage-based treatments, intake of ME was greater with cattle offered ALC because of its greater ME concentration.

Animal Performance and G:F

Little information is available on the effects of WCW silage grain content on beef cattle performance. However, the rates of performance achieved with the WCW silage-based diets in the present study were generally greater than those predicted using Eq. [9] in Ministry of Agriculture, Fisheries and Food (1984). Based on the actual DMI, ME intake, and mean BW recorded, predicted BW gains for cattle offered WCW I to IV were 750, 942, 1,044, and 1,149 g/d respectively, with only the predicted value of WCW IV being greater than the measured value. The greater than predicted growth rates achieved by the animals in this study may be due to compensatory growth over the 154-d comparison of diets because these animals were on a relatively moderate plane of nutrition before the experimental period (Hornick et al., 2000).

Linear improvements in BW and carcass gains were observed in response to increasing the grain content of WCW silage, reflecting the simultaneous increase in intake and ME content of the WCW silage. Similar trends were reported by Caplis et al. (2005) and Keane et al. (2006) with an increasing quantity of grain with GS. However, the trends reported by these authors were curvilinear in nature and may be explained by the wider range of concentrates than were used in the present study. Increasing the grain content of WCW silage resulted in a linear improvement in G:F, reflecting the observed increase in carcass gain, with a similar trend reported by Patterson et al. (2000) for increasing the proportion of concentrates in GS-based diets.

Animal performance response to feeding GS-based diets can vary greatly because of variability in digestibility and preservation characteristics. In the present study, increased rates of animal performance were obtained with GS, with the values being greater than those predicted (929 vs. 885 g/d) using the Ministry of Agriculture, Fisheries and Food (1984) equation and greater than the values reported by Caplis et al. (2005) or Walsh et al. (2008a) for comparable cattle during the finishing stage. The increased rates of growth achieved can be attributed to the increased nutritional quality of the GS, as evidenced by the greater IVDMD and NDF digestibility in the present study compared with those of Caplis et al. (2005) and Walsh et al. (2008a). This greater nutritive value of the GS in the present study also resulted in BW gains and carcass weight similar to the WCW treatments, despite cattle offered this diet exhibiting reduced DM and ME intakes.

As expected, cattle offered ALC exhibited greater rates of animal growth than those offered any of the silage-based treatments, with BW gains greater than predicted (1,335 vs. 1,258 g/d) using the Ministry of Agriculture, Fisheries and Food (1984) equation. Thus, it is not surprising that this treatment supported a superior rate of G:F compared with the other treatments.

In Vivo Apparent Diet Digestibility

Increasing the grain content of WCW silage resulted in a progressive increase in dietary DM digestibility, in agreement with the report by Walsh et al. (2009), largely reflecting the partial replacement of NDF of relatively low digestibility by almost completely digestible starch. The digestibility of the NDF fraction was markedly less in the present experiment than reported by Walsh et al. (2009); however, this may be partially due to the absence of supplemental concentrates in Walsh et al. (2009). Supplementing the diet with concentrates

increases starch intake which is known to negatively affect fiber digestion through a reduced rumen pH and subsequent inhibition of the cellulolytic organisms (Grant and Mertens, 1992).

Starch digestibility was almost complete for all WCW treatments, indicating excellent utilization of the wheat grain, with the values in the present study being marginally greater than those reported by Sinclair et al. (2003) for WCW silage of relatively similar chemical composition when using a fecal collection method. The high starch digestibility reflected adequate mechanical breakdown of the grain pericarp during harvesting (Jackson et al., 2004), resulting in extensive exposure of the cereal grain contents to the digestive processes in the rumen. The greater starch digestibility associated with the ALC diet may also be attributed to mechanical breakdown during rolling of the barley.

The quadratic response in NDF digestibility is surprising because Walsh et al. (2009) has reported that as grain content of the WCW silage increases, digestibility of the NDF fraction is depressed. Such a negative effect on fiber digestibility is principally due the reduction in pH associated with increasing the content of readily fermentable carbohydrates restricting the activity of the rumen cellulolytic bacteria (Huhtanen and Jaakola, 1993). However, in the present study NDF digestibility did not differ between the least and greatest grain silages, with the absence of a difference in rumen pH observed in Exp. 2 perhaps explaining this outcome. In comparison, the digestibility of the NDF fraction was greater for GS compared with the WCW silages, most likely attributed to a longer residence time for GS in the rumen.

Rumen Fermentation and Plasma Urea

The absence of a difference in ruminal pH with increasing grain content of WCW silage was somewhat surprising because it has been reported (Van Kessel and Russell, 1996; Lana et al., 1998; Walsh et al., 2009) that increasing the grain content of the diet usually results in a decline in rumen pH. Such a decline would most likely be the result of an increase in the supply of rapidly fermentable carbohydrates in the diet and the consequential increase in VFA and possibly lactic acid production. However, the absence of a pH response in the present study reflects the lack of difference in VFA concentration and is in agreement with Thorp et al. (2000), who reported no change in rumen pH when the ratio of barley grain to hay increased.

It has also been well established (Moe and Tyrrell, 1979; Johnson and Johnson, 1995) that altering the dietary forage-to-concentrate ratio, specifically the fiber-to-starch ratio, affects the proportion of the individual VFA in the rumen. Thus, diets that are rich in starch rather than fiber promote the formation of propionate in the rumen at the expense of acetate (France and Dijkstra, 2005). This response was confirmed in the present study by the linear decrease in the molar proportion of acetic acid and simultaneous increase in propionic acid concentration in response to increasing the grain content of WCW silage, and agrees with the findings of Walsh et al. (2009) for increasing grain inclusion with barley straw plus chaff. Increasing the grain content of WCW silage also increased rumen lactic acid concentration in agreement with Cummins (2008), who reported a greater lactic acid concentration when increasing the proportion of concentrates in GS-based diets. Relative to WCW, the molar proportion of propionic acid was increased in the rumen fluid of steers offered GS, perhaps explained by the increased intakes of lactic acid (Rinne et al., 1997) that are associated with GS.

The ruminal NH_3 and plasma urea concentrations observed indicate that adequate amounts of N were available in the experimental diets, with all plasma urea values falling within the range (3.4 to 7.3 mmol/L) defined by Castejon and Leaver (1994) as being normal. The decrease in rumen NH_3 observed in response to increasing the grain content of WCW silage may reflect an increase in microbial N synthesis, facilitated by the increase in starch intake (Hristov and Ropp, 2003).

Methane Emissions

In the present study, methane measurements were carried out using the SF_6 tracer technique. Initially developed as a method of methane measurement for animals at pasture, it allows for sampling of a large number of animals while maintaining normal animal production conditions during sampling (indoors and outdoors), with relatively little disruption of behavioral patterns, [i.e., feeding and lactation (McGinn et al., 2006)]. When discussing methane emissions associated with dietary regimens, it is important to consider the unit of expression. Expressing methane relative to DMI or saleable product also provides information on aspects of efficiency. In the present study, the unit to which methane was expressed determined the relationship between the experimental treatments. Increasing the grain content of WCW silage resulted in a reduction in methane output per kilogram of DMI, with several possible explanations perhaps explaining this outcome. First, increasing the starch content of the diet resulted in a shift in rumen fermentation toward the production of propionic acid at the expense of acetic acid. The production of propionic acid is a hydrogen-utilizing process, which thereby deprives the methogenic bacteria of the hydrogen necessary for methane production (Moss et al., 2000). This suggestion is supported by the pattern in rumen VFA production observed in Exp. 2. Second, the increasing DMI observed from WCW I to III may have resulted in an increase in the rate of digesta outflow from the rumen, rendering less time available for microbial fermentation of the ingested feed to occur, and thereby limiting the quantity of methane produced (Johnson and Johnson, 1995; Yan et al., 2000).

One frequently discussed strategy for methane abatement is an improvement in animal productivity. This

can be achieved through several pathways, including nutritional manipulation, genetic selection, or improved animal management (Boadi et al., 2004). In the present study, nutritional manipulation, through increasing the grain content of WCW silage, resulted in a 0.39 reduction in methane output per kilogram of carcass gain, principally because of the observed linear improvement in the rate of carcass gain. This significant reduction illustrates the potential of improving feed efficiency and performance as effective pathways to reduce the methane output from beef cattle. This trend is similar to that reported by Lovett et al. (2003), who observed reductions in methane output per unit of saleable product when increasing the grain-to-GS ratio of the diet of beef cattle.

As well as the negative environmental consequences associated with ruminant methane production, the latter represents a sizeable loss of productive energy for the animal, ranging from 0.02 to 0.12 of GE intake (Moss et al., 2000). This loss of productive energy may indirectly have significant financial implications for beef producers and may provide an incentive for adopting mitigation strategies that can reduce methane output and improve animal performance. In the present study, although no significant linear or quadratic responses in methane output proportionate to GE intake were observed in response to increasing the grain content of WCW silage, WCW IV was less than the other wheat treatments. This suggests that a dietary threshold amount of starch must be achieved to sufficiently stimulate the production of glucogenic VFA to a concentration at which they would provide a viable alternative hydrogen sink to methanogenesis (Lovett et al., 2005), thus reducing methane losses.

From the data in the present study, it is evident that increasing the grain content of WCW silage can reduce methane emissions relative to DMI and carcass gain, making the inclusion of high-grain WCW silages in feeding regimens a potentially viable option for methane abatement. Furthermore, improved agronomic practices and breeding programs allow for WCW to be grown in areas previously thought unsuitable for arable crops, thus increasing its attractiveness as a substitute for GS in winter feeding systems. However, it is important to consider the costs, both environmental and financial, involved in the production and feeding of WCW silage.

Total daily methane emission from cattle offered GS were similar to those offered WCW-based treatments, in agreement with the findings of McCourt et al. (2007). Methane losses proportionate to GE intake for GS were, however, as expected for forages and were at the upper end of the range reported by Moss et al. (2000), although the values in the present study were less than those reported by Yan et al. (2000) for GS-based diets. This difference may be attributable to the greater DM and NDF digestibility and ultimately greater nutritional quality of the GS in the present study. The greater methane output proportional to GE intake for GS than WCW is perhaps not surprising given the greater content of starch present in the WCW diets. In addition, it is important to note the absence of a difference between WCW and GS for methane output per kilogram of carcass gain, reflecting the increased performance achieved by the GS treatment.

Irrespective of the unit of expression, cattle offered ALC exhibited less methane output than those offered any of the silage-based treatments. This response can be attributed to the unfavorable conditions that were created for methanogenesis by increased starch intakes, as described previously. High-concentrate diets also support increased growth rates, with animals achieving their slaughter weights at earlier ages, thus facilitating reduced lifetime emissions.

In conclusion, increasing the grain content of WCW silage reduced methane output from finishing beef steers per kilogram of DMI and per kilogram of carcass gain while simultaneously improving growth rates. The overall trend in this study suggests that increasing the starch content of the diet can serve as an effective method for enteric methane abatement that should not compromise animal performance. This is evident from the relatively large methane output associated with the silage-based treatments and the decreased methane output associated with the starch-rich ALC treatment. However, to extrapolate the results of this study and assess the full environmental impact of the implementation of these feeding regimens, a complete life-cycle analysis must be carried out to ascertain the total greenhouse gas emissions associated with these feeding regimens.

LITERATURE CITED

Agriculture and Food Research Council (AFRC). 1993. Energy and Protein Requirements of Ruminants. CAB Int., Wallingford, UK.

Allen, M. S. 1996. Physical constraints on voluntary intake of forages by ruminants. J. Anim. Sci. 74:3063–3075.

Beauchemin, K. A., M. Kreuzer, F. O'Mara, and T. A. McAllister. 2008. Nutritional management for enteric methane abatement: A review. Aust. J. Exp. Agric. 48:21–27.

Boadi, D., C. Benchaar, J. Chiquette, and D. Massé. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. Can. J. Anim. Sci. 84:319–335.

Caplis, J., M. G. Keane, A. P. Moloney, and F. P. O'Mara. 2005. Effects of supplementary concentrate level with grass silage, and separate or total mixed ration feeding, on performance and carcass traits of finishing steers. Ir. J. Agric. Food Res. 44:27–43.

Castejon, M., and J. D. Leaver. 1994. Intake and digestibility of urea-treated whole-crop wheat and live-weight gain by dairy heifers. Anim. Feed Sci. Technol. 46:119–130.

Commission of the European Communities. 1982. Commission of the European Communities (Beef Carcass Classification) Regulations. Council Regulations 1358/80, 1208/81, 1202/82. Commission Regulations 2930/81, 563/82, 1557/82. Commission of the European Communities, Brussels, Belgium.

Conry, M. J., and J. J. Hogan. 2001. Comparison of Cereals Grown Under High (Conventional) and Low (Reduced) Input Systems. Teagasc, Dublin, Ireland.

Cummins, B. 2008. Alternative strategies for improving the efficiency of utilisation of forage concentrates by finishing cattle. PhD Thesis. University College Dublin, Dublin, Ireland.

France, J., and J. Dijkstra. 2005. Volatile fatty acid production Pages 157–175 in Quantitative Aspects of Ruminant Digestion and Metabolism. 2nd ed. J. Dijkstra, J. M. Forbes, and J. France, ed. CABI Publ., Wallingford, Oxfordshire, UK.

Galyean, M. L., and F. N. Owens. 1991. Effects of diet composition and level of feed intake on site and extent of digestion in ruminants. Pages 483–514 in Physiological Aspects of Digestion and Metabolism in Ruminants. T. Tsuda, Y. Sasaki, and R. Kawashima, ed. Academic Press Inc., San Diego, CA.

Grant, R. J., and D. R. Mertens. 1992. Influence of buffer pH and raw corn starch addition on in vitro fiber digestion kinetics. J. Dairy Sci. 75:2762–2768.

Hornick, J. L., C. Van Eenaeme, O. Gérard, I. Dufrasne, and L. Istasse. 2000. Mechanisms of reduced and compensatory growth. Domest. Anim. Endocrinol. 19:121–132.

Hristov, A. N., and J. K. Ropp. 2003. Effect of dietary carbohydrate composition and availability on utilization of ruminal ammonia nitrogen for milk protein synthesis in dairy cows. J. Dairy Sci. 86:2416–2427.

Huhtanen, P., and S. Jaakola. 1993. The effects of forage preservation method and proportion of concentrate on digestion of cell wall carbohydrates and rumen digesta pool size. Grass Forage Sci. 48:155–165.

Huhtanen, P., M. Rinne, and J. Nousiainen. 2007. Evaluation of the factors affecting silage intake of dairy cows: A revision of the relative silage dry-matter intake index. Animal 1:758–770.

Jackson, M. A., R. J. Readman, J. A. Huntington, and L. A. Sinclair. 2004. The effects of processing at harvest and cutting height of urea-treated whole-crop wheat on performance and digestibility in dairy cows. Anim. Sci. 78:467–476.

Johnson, K. A., M. Huyler, H. Westburg, B. Lamb, and P. Zimmerman. 1994. Measurement of methane emissions from ruminant livestock using a SF_6 tracer technique. Environ. Sci. Technol. 28:359–362.

Johnson, K. A., and D. E. Johnson. 1995. Methane emissions from cattle. J. Anim. Sci. 73:2483–2492.

Keady, T. W. J. 2005. Ensiled maize and whole-crop wheat forages for beef and dairy cattle: Effects on animal performance. Pages 65–82 in Proc. XIV Int. Silage Conf., Belfast, N. Ireland. R. S. Park and M. D. Stronge, ed. Wageningen Acad. Publ., Wageningen, the Netherlands.

Keane, M. G., M. J. Drennan, and A. P. Moloney. 2006. Comparison of supplementary concentrate levels with grass silage, separate or total mixed ration feeding, and duration of finishing in beef steers. Livest. Sci. 103:169–180.

Keating, T., and P. O'Kiely. 1997. Irish farm silage 1996–1996. Page 123 in Proc. Agric. Res. Forum, Tullamore, Ireland. Teagasc, Dublin, Ireland.

Kennelly, J. J., and Z. G. Weinberg. 2003. Small grain silage. Pages 749–779 in Silage Science and Technology. D. R. Buxton, R. E. Muck, and J. H. Harrison, ed. Am. Soc. of Agron., Crop Sci. Soc. of Am., Soil Sci. Soc. of Am., Madison, WI.

Lana, R. P., J. B. Russell, and M. E. Van Amburgh. 1998. The role of pH in regulating ruminal methane and ammonia production. J. Anim. Sci. 76:2190–2196.

Lovett, D., S. Lovell, L. Stack, J. Callan, M. Finlay, J. Connolly, and F. P. O'Mara. 2003. Effect of forage/concentrate ratio and dietary coconut oil level on methane output and performance of finishing beef heifers. Livest. Prod. Sci. 84:135–146.

Lovett, D. K., L. J. Stack, S. Lovell, J. Callan, B. Flynn, M. Hawkins, and F. P. O'Mara. 2005. Manipulating enteric methane emissions and animal performance of late-lactation dairy cows through concentrate supplementation at pasture. J. Dairy Sci. 88:2836–2842.

Mayne, C. S., and P. O'Kiely. 2005. An overview of silage production and utilisation in Ireland (1950–2005). Pages 19–34 in Proc. XIV Int. Silage Conf., Belfast, N. Ireland. R. S. Park and M. D. Stronge, ed. Wageningen Acad. Publ., Wageningen, the Netherlands.

McCourt, A. R., T. Yan, and C. S. Mayne. 2007. Effect of forage type on methane production from dairy cows. Page 48 in Proc. Ann. Meet. Br. Soc. Anim. Sci., Southport, UK. Nottingham Univ. Press, Nottingham, UK.

McGee, M., P. O'Kiely, and E. G. O'Riordan. 2006. Intake, growth, carcass traits and plasma metabolites in finishing steers offered contrasting concentrate energy sources at two feeding levels. Page 101 in Proc. Agric. Res. Forum, Tullamore, Ireland, Teagasc, Dublin, Ireland.

Mc Geough, E. J., P. O'Kiely, P. A. Foley, K. J. Hart, T. M. Boland, and D. A. Kenny. 2010. Methane emissions, feed intake, and performance of finishing beef cattle offered maize silages harvested at four different stages of maturity. J. Anim. Sci. 88:1479–1491. doi:10.2527/jas.2009-2380

McGinn, S. M., K. A. Beauchemin, A. D. Iwaasa, and T. A. McAllister. 2006. Assessment of the sulphur hexafluoride (SF_6) tracer technique for measuring enteric methane emissions from cattle. J. Environ. Qual. 35:1686–1691.

Ministry of Agriculture, Fisheries and Food. 1984. Energy allowances and feeding systems for ruminants. Tech. Bull. 33. Her Majesty's Stationery Office, London, UK.

Moe, P. W., and H. F. Tyrrell. 1979. Methane production in dairy cows. J. Dairy Sci. 62:1583–1586.

Moss, A. R., J.-P. Jouany, and J. Newbold. 2000. Methane production by ruminants: Its contribution to global warming. Ann. Zootech. 49:231–253.

O'Kiely, P., and A. P. Moloney. 1995. Performance of cattle offered whole-crop barley or wheat silage. Ir. J. Agric. Food Res. 34:13–24.

Patterson, D. C., R. W. J. Steen, C. A. Moore, and B. W. Moss. 2000. Effects of the ratio of silage to concentrates in the diet on the performance and carcass composition of continental bulls. Anim. Sci. 70:171–179.

Rinne, M., S. Jaakola, and P. Huhtanen. 1997. Grass maturity effects on cattle fed silage-based diets. 1. Organic matter digestion, rumen fermentation and nitrogen utilization. Anim. Feed Sci. Technol. 67:1–17.

Sinclair, L. A., R. G. Wilkinson, and D. M. R. Ferguson. 2003. Effects of crop maturity and cutting height on the nutritive value of fermented whole crop wheat and milk production in dairy cows. Livest. Prod. Sci. 81:257–269.

Thorp, C. L., A. R. G. Wylie, R. W. J. Steen, C. Shaw, and J. D. McEvoy. 2000. Effects of incremental changes in forage:concentrate ratio on plasma hormone and metabolite concentrations and products of rumen fermentation in fattening beef steers. Anim. Sci. 71:93–109.

Van Kessel, J. A. S., and J. B. Russell. 1996. The effect of pH on ruminal methanogenesis. FEMS Microbiol. Ecol. 20:205–210.

Van Keulen, J., and B. A. Young. 1977. Evaluation of acid-insoluble ash as a natural marker in ruminant digestibility studies. J. Anim. Sci. 44:282–287.

Walsh, K., P. O'Kiely, A. P. Moloney, and T. M. Boland. 2008a. Intake, digestibility, rumen fermentation and performance of beef cattle fed diets based on whole-crop wheat or barley harvested at two cutting heights relative to maize silage or ad libitum concentrates. Anim. Feed Sci. Technol. 144:257–278.

Walsh, K., P. O'Kiely, A. P. Moloney, and T. M. Boland. 2008b. Intake, performance and carcass characteristics of beef cattle offered diets based on whole-crop wheat or forage maize relative to grass silage or ad libitum concentrates. Livest. Sci. 116:223–236.

Walsh, K., P. O'Kiely, H. Z. Taweel, M. McGee, A. P. Moloney, and T. M. Boland. 2009. Intake, digestibility and rumen characteristics in cattle offered whole-crop wheat or barley silages of contrasting grain to straw ratios. Anim. Feed Sci. Technol. 148:192–213.

Yan, T., R. E. Agnew, F. J. Gordon, and M. G. Porter. 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. Livest. Prod. Sci. 64:253–263.