Journal of Agricultural Science (2013), **151**, 347–367. © Cambridge University Press 2012
doi:10.1017/S0021859612000342

CROPS AND SOILS RESEARCH PAPER

Yield, nutritive value and ensilage characteristics of whole-crop maize, and of the separated cob and stover components – nitrogen, harvest date and cultivar effects

J. P. LYNCH[1,2], P. O'KIELY[1]* AND E. M. DOYLE[2]

[1] *Animal and Grassland Research and Innovation Centre (AGRIC), Teagasc, Grange, Dunsany, Co. Meath, Ireland*
[2] *School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland*

(*Received 13 October 2011; revised 6 February 2012; accepted 14 March 2012; first published online 13 April 2012*)

SUMMARY

The objectives of the present study were to determine the effects of nitrogen (N) application rate, harvest date and maize cultivar on the yield, quality and the subsequent conservation characteristics of whole-crop, cob and stover silages. The experiment was organized in a spilt-plot design, with harvest date (15 September, 6 October and 27 October) as the main plot, and a three (maize cultivars: Tassilo, Andante and KXA 7211) × two (N application rate: 33 and 168 kg N/ha) factorial arrangement of treatments as the sub-plot, within three replicate blocks, and was conducted at Grange, Dunsany, Co. Meath, Ireland in 2009. The three harvest dates represented early, normal and late harvests, respectively, for a midland site in Ireland. Of the three maize cultivars selected, cvars Tassilo and Andante represent conventional cultivars sown by commercial livestock farmers in Ireland, while cvar KXA 7211 is categorized as a high biomass cultivar. No effect of N application rate was observed on the dry matter (DM) yield, nutritive value or ensiling characteristics of maize whole-crop or cob. Whole-crop and stover harvested on the later date had a lower digestible DM (DDM) content and the silages underwent a more restricted fermentation, compared to silages produced from herbage harvested on earlier dates. Cob silages produced from crops harvested on 15 September had lower DDM content and higher DM loss during ensiling than later harvest dates. Despite higher whole-crop DM yields, the later maturing cultivar KXA 7211 did not improve the DM yields of cob and also resulted in increased DM losses from the ensilage of cob, when compared with the other cultivars. In addition to the DM yield and nutritive value of forage maize at harvest, the subsequent fermentation profile during ensilage influences the optimum choice of cultivar and date for crop harvest in a maize silage production system.

INTRODUCTION

Forage maize (*Zea mays* L.) silage has the potential to improve ruminant performance compared with many grass silages (Fitzgerald & Murphy 1999; Phipps *et al.* 2000; Keady *et al.* 2007). To fulfil a worthwhile role in commercial farming, this whole-crop silage requires a high starch concentration and thus a high proportion of well-developed cob because the moderate digestibility of the stover component will only support rates of animal performance similar to what would be achieved with average quality grass silage (O'Kiely & Moloney 1995).

In recent times, the adoption of technologies such as plastic mulch and earlier-maturing cultivars, which help counteract the limitations of unfavourable climatic conditions, has facilitated increases in the achieved yield and quality of forage maize grown in marginal locations (Crowley 1998; Farrell & Gilliland 2011). Despite these developments, there remains a requirement to optimize the forage maize production system in marginal locations in order to avoid low crop yield or poor nutritive value, and to manage the subsequent ensiling process to minimize quantitative or qualitative losses. Finneran *et al.* (2012) reported that whole-crop

* To whom all correspondence should be addressed. Email: padraig.okiely@teagasc.ie

maize could either be the cheapest or the most expensive home-produced alternative feed to grazed grass, depending on how factors such as climate, soil and management impact on crop yield and nutritive value, and on the efficiency of its conservation.

Whole-crop forage maize production systems typically require high inputs of fertilizer to support the production of large yields of plant biomass (Allen *et al.* 2003). Previous studies in climates that facilitate high yields of forage maize have reported increased whole-crop and grain yield with increased nitrogen (N) application rates, with optimum inputs in the range 150–200 kg N/ha (Cox & Cherney 2001; Trindade *et al.* 2009; Masoero *et al.* 2011). However, legislative restrictions detailed in Statutory Instrument 101 (2009) state that the amount of livestock manure applied in a year must not exceed 170 kg organic N/ha which, when spread in the form of cattle slurry, provides *c.* 49 kg available N/ha. Therefore, up to 0·70 of applied N in a typical maize production system is likely to be in the form of chemical fertilizer, which contributes a significant expense in the production cost of the crop.

Studies investigating the effects of N application rate on the yield and nutritive value of maize grown in climatically marginal locations are not widely available. In addition, previous studies on forage maize grown in Ireland and Britain focused primarily on the effects of crop management factors on whole-crop yield and quality at harvest time, and on the proportion of cob present (Easson & Fearnehough 2000; Keane 2002; Keane *et al.* 2003), with little research investigating the impacts they have on the conservation characteristics of ensiled maize. Information on the effects that crop management has on the ensilage of forages is required as this process can alter their nutritional value and may cause qualitative and quantitative losses through effluent production, respiration and fermentation (McDonald *et al.* 1991). Since the ensiling properties of cob and stover may differ, and with the relative contribution of these two components of the whole-crop varying between cultivars, it is important to understand the impact that factors such as N application rate, harvest date and cultivar selection have on the cob and stover components of the freshly harvested whole-crop and on the silages produced from these components.

The objectives of the present study were to determine the effects of N application rate, harvest date and cultivar on the yield, quality and the subsequent conservation characteristics of whole-crop, cob and stover silages.

MATERIALS AND METHODS

Experimental design

The experiment was organized in a spilt-plot design, with harvest date (15 September, 6 October and 27 October) as the main plot, and a three (maize cultivars: Tassilo, Andante and KXA 7211)×two (N application rate: 33 and 168 kg N/ha) factorial arrangement of treatments as the sub-plot, within three replicate blocks. The three harvest dates represented early, normal and late harvests, respectively, for a midland site in Ireland. Of the three maize cultivars selected, Tassilo and Andante represent conventional cultivars sown by commercial livestock farmers in Ireland, while KXA 7211 is categorized as a high biomass cultivar.

Experimental site, crop production and management

The experimental site (Grange, Dunsany, Co. Meath; 53°30′N, 6°39′W, 83 m asl) had been used to grow maize in 2008 and had previously been in permanent pasture for 30 years. The soil type was from the slowly permeable Ashbourne series of the gley grouping (Finch *et al.* 1983).

Cattle slurry was applied to all plots prior to ploughing on 1 April 2009, at a rate calculated to provide 33 kg available N/ha. Inorganic N was applied at two rates (low, 0 kg N/ha; high, 135 kg N/ha in the form of calcium ammonium nitrate (CAN; 275 g N/kg)) 4 h prior to sowing. After seedbed preparation, three replicate blocks, each with 18 four-row plots (individual plots were 20·0 × 3·81 m) were sown under plastic mulch (1·37 m wide, 6 µm thick film which covered two rows of seed; X-tend transparent photodegradable polythene, I.P Ltd, Gorey, Co. Wexford, Ireland) on 13 May 2009 with a Samco 4 Row 4700 SP seed drill at a depth of *c.* 50 mm and at a rate of 100 000 seeds/ha. The row spacing was 0·85 m between the two central rows, with 0·72 m separating these and the outer rows of a plot. Herbicide (Calaris; Syngenta Crop Protection UK Ltd, Cambridge, UK; 1 litre/ha) was applied at sowing and on 7 July.

Onatrio heat units (OHU) were calculated using meteorological data recorded within 0·5 km of the crop using the instruments and standards described by Fitzgerald & Fitzgerald (2004).

Harvesting and ensiling

On each harvest date, the two central rows were cut using a reciprocating blade mower (Agria 5400 KL, Nottingham, UK) at a stubble height of 100 mm and weighed. To determine the proportion of the major plant components harvested, 30 plants were randomly selected, separated into cob (rachis and kernels) and stover (remainder of plant after cob removal) and weighed.

A representative sample of the remaining plants was taken to produce 10 kg of each of whole-crop, and separated cob and stover. Whole-crop and stover samples were subsequently precision-chopped (set to a theoretical chop length of 19 mm; Pottinger Mex VI, Grieskirchen, Austria), while cobs were chopped in a food processor (Müller MTK 204 special, Saarbrücken, Germany). Representative 5 kg sub-samples of each chopped material were ensiled in a laboratory silo (O'Kiely & Wilson 1991) for 130 days at *c.* 15 °C. Samples of whole-crop, cob and stover were also taken at pre-ensiling and stored at –20 °C prior to chemical analysis.

Any effluent produced from the laboratory silo was collected and weighed after 3, 10, 35 and 130 days. After 130 days ensilage, the silages were weighed, aseptically mixed and sampled for chemical and microbial analyses.

Aerobic stability

Aerobic stability was determined by placing *c.* 2·7 kg of each silage into a polystyrene box (250 mm thick; 590 × 390 × 220 mm) lined with polythene and loosely covered with a polystyrene lid. A thermocouple was placed in the centre of each silage sample. The temperature of the silage was recorded on an hourly basis over an 8-day period by a data logger (SQ ELTEK 80T; Eurolec Instrumentation Ltd, Dundalk, Ireland). Reference temperatures were obtained from containers of water stored beside the boxes of silage. The indices of aerobic stability and deterioration were expressed as (i) accumulated temperature rise above the reference temperature during 120 h exposure to air and (ii) hours elapsed until the temperature rose more than 2 °C higher than the reference temperature.

Chemical analysis

Samples of whole-crop, cob and stover were homogenized using a food processor (Muller MKT 204 Special Food Processor, Saarbrücken, Germany). The dry matter (DM) concentration of samples pre- and post-ensiling was determined by drying in an oven with forced air circulation at 98 and 85 °C for 16 h, respectively, with the latter values being corrected for loss of volatile components using the procedure of Porter & Murray (2001). Samples oven-dried at 40 °C for 48 h were ground through a hammer mill (Willey Mill, Athur H. Thomas, Philadelphia, PA, USA) that had a screen with 1 mm apertures prior to chemical analysis. The digestible DM (DDM) content was analysed as described by Tilley & Terry (1963), with the final residue isolated by filtration (through Whatman GF A, pore size 1·6 µm; Maidstone, England) instead of by centrifugation. Starch was determined using the Megazyme total starch assay procedure (McCleary *et al.* 1994). The concentration of cold-water soluble carbohydrates (WSC) was analysed using the automated anthrone method (Thomas 1977) and crude protein (CP; total N × 6·25) was determined using a LECO FP-528N analyser (Leco, St. Joseph, MI, USA) by measuring the thermal conductivity of N present in a sample following total combustion at 900 °C, based on the methods of the Association of Analytical Chemists (AOAC) 900-03 (AOAC 1990). Both neutral detergent fibre (NDF; included α-amylase and sodium sulphite) and acid detergent fibre (ADF) were analysed using the ANKOM filter bag technique (ANKOM 2006*a*, *b*) based on the analytical method of Van Soest *et al.* (1991) and were expressed exclusive of ash. Ash concentration was determined by complete combustion in a muffle furnace at 550 °C for 5 h, while buffering capacity (BC) was analysed using the method of Playne & McDonald (1966).

Aqueous extracts were removed from silage using a hydraulic press and the pH was obtained using a pH electrode (Hanna Instruments, Leighton Buzzard, UK; HI98127). The volatile fatty acids (VFA) and ethanol concentrations were measured with a gas chromatograph (Shimadzu GC 17-A, Milton Keynes, UK) with a flame ionization detector and fitted with a chromopack column (2·4 m × 5 mm (outside diameter) 3 mm (internal diameter) glass with T_{max} 200 °C on chrom WHP 80–100 mesh) using the method of Ranfft (1973). Lactic acid concentration was analysed using the SP-Ace Clinical Chemical Analyser (Alfa Wassermann, NJ, USA, and the L-lactic acid UV-method test kit, Roche/R-Biopharm catalogue number 101309084035, Darmstadt, Germany) and D-lactate concentration was determined using the enzyme D-lactate dehydrogenase (Roche/R-Biopharm catalogue number 1016941001). Concentrations of ammonia (NH_3) were determined using the SP-Ace Clinical Chemical Analyser and the Thermo Electron Infinity ammonia liquid stable reagent kinetic method (Waltham, MA, USA).

Microbial analysis

Silage samples were initially stored at 4 °C, and isolation of microbes from the herbage commenced within 4 h of silo opening. A 30 g sample of silage was added to 270 ml of peptone water (1 g/l H_2O; Oxoid, LP0037) and homogenized for 3 min in a stomacher blender (Colworth stomacher 400, A. J. Seward & Co. Ltd, London), with a subsequent 1 ml aliquot serially diluted in peptone water. Media consisting of De Man, Rogosa and Sharpe agar (MRS, Oxoid, CM361B) and nystatin (20 ml/l, Sigma, N1638) were used for the enumeration of lactic acid bacteria (LAB), while malt extract agar (Oxoid, CM0059B), streptomycin (100 mg/l, Sigma, S9137) and chloramphenicol (100 mg/l, Sigma, C0378) were used to enumerate yeast using the double-layer pour plate method. Following incubation at 30 °C the colony-forming units on each plate were enumerated and the number of micro-organisms per gram of herbage expressed on a $\log_{10}$ basis.

Statistical analysis

Data were analysed as a split-plot design using a model that accounted for replicated blocks and harvest date as the main plot and a three × two factorial arrangement of cultivar and N application rate in the sub-plot and their interactions, using the PROC GLM procedure of the SAS Version 9.1 statistical program (SAS 2002). Treatment contrasts were made using the Fischer least significant differences test.

RESULTS

Yield and DM concentration

On average, no effect ($P>0{\cdot}05$) of N application rate was observed on the DM yield or DM concentration of whole-crop or cob, while the proportion of cob in whole-crop DM was also unaffected (Table 1). Cultivars grown under the high N application rate had a higher ($P<0{\cdot}05$) stover DM yield than low N plots.

The DM yields of both whole-crop and stover were unaffected ($P>0{\cdot}05$) by harvest date, while the cob DM yield of cultivars harvested on 15 September was lower ($P<0{\cdot}01$) than at later harvest dates (Table 1). The DM concentration of both whole-crop and cob harvested on 27 October was higher ($P<0{\cdot}01$) than on earlier harvest dates, whereas stover harvested on 6 October had a lower ($P<0{\cdot}05$) DM concentration than stover harvested on 15 September. The proportion of cob in whole-crop DM increased ($P<0{\cdot}05$) with later harvesting.

The cultivar KXA 7211 had a higher ($P<0{\cdot}01$) DM yield of whole-crop and stover than the other cultivars, although no significant difference ($P>0{\cdot}05$) for whole-crop DM yield was observed between KXA 7211 and Andante harvested on 15 September. The DM concentration of whole-crop and cob was higher ($P<0{\cdot}01$) for Andante and lower ($P<0{\cdot}05$) for KXA 7211 compared with Tassilo, although there was no difference ($P>0{\cdot}05$) between the DM concentration of cob from Andante and Tassilo harvested on 15 September. KXA 7211 had a lower ($P<0{\cdot}01$) proportion of cob in whole-crop DM, compared with the other cultivars.

Pre-ensilage chemical composition

No main effect ($P>0{\cdot}05$) of N application rate was observed on the DDM content, or the WSC, starch, NDF, ADF, hemicellulose or ash concentrations of whole-crop, cob or stover. However, cvar Tassilo harvested on 15 September and Andante harvested on 27 October had higher ($P<0{\cdot}05$) cob DDM content when grown on plots with a high N application rate (Tables 2 and 3). The CP concentration of whole-crop, cob and stover was higher ($P<0{\cdot}05$) and the BC of whole-crop and stover was lower ($P<0{\cdot}01$) for crops grown on plots with a high N application rate, although the BC of whole-crop from KXA 7211 harvested on 15 September and 27 October was lower ($P<0{\cdot}05$) when grown on plots with a low N application rate.

The DDM content of whole-crop and stover was lower ($P<0{\cdot}05$) on 27 October than on earlier harvest dates, while no effect ($P>0{\cdot}05$) of later harvesting was observed on the DDM content of cob. The WSC concentration of whole-crop, cob and stover cultivars harvested on 27 October was lower ($P<0{\cdot}05$) than earlier harvest dates. The starch concentration of whole-crop and cob increased with later harvesting ($P<0{\cdot}05$), with the exception of Andante which did not have a significant increase in starch between 6 and 27 October. Later harvesting decreased ($P<0{\cdot}01$) the NDF, ADF, hemicellulose and ash concentrations of cob while the opposite ($P<0{\cdot}05$) was observed for stover. The NDF, ADF and hemicellulose concentrations of whole-crop harvested on 6 October were

Table 1. *DM yield (t/ha), DM concentration (g/kg) and cob content of forage maize (g cob/kg whole plant, DM basis) whole-crop, cob and stover at the time of harvest – harvest date, cultivar and N application rate effects*

			Whole crop			Cob		Stover	
Harvest (H)	C*	N†	DM yield	DM	Cob content	DM yield	DM	DM yield	DM
15 Sep	T	Low	7·7	199	333	2·5	272	5·2	194
	T	High	8·9	192	241	2·2	245	6·6	200
	A	Low	10·7	217	275	3·0	256	7·8	209
	A	High	10·8	229	325	3·5	275	7·3	202
	K	Low	10·4	195	268	2·9	191	7·5	202
	K	High	11·0	197	206	2·2	157	8·7	197
6 Oct	T	Low	9·5	216	450	4·2	391	5·2	176
	T	High	11·0	220	450	5·0	391	6·1	171
	A	Low	10·3	246	500	5·1	440	5·1	177
	A	High	10·8	222	381	4·1	429	6·7	186
	K	Low	11·7	208	341	4·0	267	7·7	189
	K	High	12·8	207	348	4·5	248	8·3	177
27 Oct	T	Low	10·1	243	539	5·4	451	4·6	177
	T	High	9·4	236	592	5·6	453	3·9	169
	A	Low	9·9	268	516	5·1	480	4·8	203
	A	High	9·8	258	508	5·0	483	4·9	204
	K	Low	13·0	227	457	5·9	349	7·0	182
	K	High	13·2	236	445	5·8	352	7·4	199
S.E.M.									
H (4 D.F.)			0·32	4·1	26·8	0·26	8·8	0·36	3·4
C (18 D.F.)			0·28	2·8	14·1	0·19	4·8	0·22	2·8
N (18 D.F.)			0·26	2·1	12·4	0·17	3·8	0·21	2·6
H × C × N (18 D.F.)			0·77	6·2	37·2	0·51	11·4	0·64	7·9

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.
† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

lower ($P<0·05$) than on other harvest dates, while the ash concentration of whole-crop was unaffected ($P>0·05$) by harvest date. Whole-crop, cob and stover harvested on 15 September had a higher ($P<0·05$) CP concentration than on later harvest dates, while the BC of cob and stover harvested on 15 September was higher ($P<0·001$) and lower ($P<0·01$), respectively, than on later harvest dates.

Whole-crop, cob and stover from Andante had a lower ($P<0·05$) DDM content, while whole-crop and stover from Tassilo had a higher ($P<0·05$) DDM content, compared with the other cultivars. The WSC concentration of whole-crop, cob and stover from Andante was lower ($P<0·05$) than the other cultivars, although no difference in the WSC concentration of whole-crop or stover was observed between Andante and Tassilo harvested on 27 October. The starch concentration of whole-crop and cob from KXA 7211 was lower ($P<0·001$) than the other cultivars, while cobs from Andante had a higher ($P<0·001$) starch content than the other cultivars. The NDF, ADF, hemicellulose and ash concentrations of cob from Andante were lower ($P<0·05$) than KXA 7211, while the opposite was observed ($P<0·01$) for stover. The CP concentration of whole-crop was unaffected ($P>0·05$) by cultivar, whereas whole-crop from KXA 7211 had a higher ($P<0·05$) BC than the other cultivars. Cobs from KXA 7211 had a higher ($P<0·05$) CP concentration and BC than the other cultivars, while stover from KXA 7211 had a lower ($P<0·001$) CP concentration.

Post-ensilage chemical composition (non-fermentation)

Cob silages produced from crops grown on plots with a higher N application rate had higher ($P<0·05$) NDF and ADF concentrations. However, the NDF and ADF concentrations of both whole-crop and stover silages and the WSC concentration of both whole-crop and cob silages were unaffected ($P>0·05$) by N application

Table 2. *DDM (g/kg), WSC, starch and CP concentrations (g/kg DM) and BC (mEq/kg DM) of maize whole-crop, cob and stover at the time of harvest – harvest date, cultivar and N application rate effects*

			Whole-crop					Cob					Stover				
Harvest (H)	C*	N†	DDM	WSC	Starch	CP	BC	DDM	WSC	Starch	CP	BC	DDM	WSC	Starch	CP	BC
15 Sep	T	Low	755	175	86	80	237	762	117	200	91	154	705	197	18	71	261
	T	High	750	220	59	85	238	788	129	182	95	171	724	201	14	76	244
	A	Low	687	155	72	80	245	784	97	241	97	169	612	149	9	72	262
	A	High	723	149	83	83	242	761	84	250	91	156	656	186	10	76	261
	K	Low	738	201	21	75	278	859	168	25	113	351	677	208	18	60	252
	K	High	686	185	18	75	252	852	177	44	115	312	683	181	10	70	254
6 Oct	T	Low	767	150	193	69	246	794	112	446	83	110	682	177	23	58	305
	T	High	764	137	214	76	221	810	106	455	90	116	659	166	22	70	282
	A	Low	720	108	207	69	240	786	75	548	79	113	599	77	23	69	345
	A	High	705	150	187	76	238	770	74	536	83	109	604	98	18	70	297
	K	Low	756	221	96	70	246	801	157	279	92	144	658	190	11	56	285
	K	High	730	224	73	71	259	802	144	292	95	153	645	152	13	58	271
27 Oct	T	Low	690	41	259	73	236	794	36	579	86	109	627	42	39	71	338
	T	High	698	52	221	75	240	799	40	569	88	109	652	53	23	70	307
	A	Low	632	33	250	67	251	744	26	614	79	106	575	23	21	59	336
	A	High	644	36	179	72	227	783	29	612	84	108	564	26	9	69	278
	K	Low	682	122	122	69	272	816	89	492	88	131	614	79	26	55	310
	K	High	681	102	150	73	223	823	93	499	91	139	615	101	30	62	282
S.E.M.																	
H (4 D.F.)			8·6	16·1	6·6	0·6	3·0	4·3	1·6	4·3	1·2	5·2	6·3	15·3	3·3	1·1	3·9
C (18 D.F.)			7·2	6·9	5·9	1·5	3·7	4·3	2·8	6·5	0·8	3·6	6·1	6·5	3·3	1·4	6·3
N (18 D.F.)			6·3	4·6	6·0	1·1	2·8	2·8	1·4	4·4	0·7	3·9	6·9	5·9	2·0	0·8	5·0
H × C × N (18 D.F.)			18·0	13·9	18·0	3·4	8·4	8·4	4·3	13·2	2·0	11·7	19·7	17·8	6·0	2·4	14·9

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.

† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

Table 3. *Structural carbohydrate and ash concentrations (g/kg DM) of forage maize whole-crop, cob and stover at the time of harvest – harvest date, cultivar and N application rate effects*

			Whole-crop				Cob				Stover			
Harvest (H)	C*	N†	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash
15 Sep	T	Low	514	275	240	49	494	230	265	23	580	328	252	58
	T	High	527	279	248	48	487	230	256	24	569	310	259	59
	A	Low	569	323	246	55	447	213	234	24	626	370	256	68
	A	High	570	308	262	55	474	231	243	23	608	359	249	68
	K	Low	572	327	245	57	499	228	271	34	606	351	255	60
	K	High	598	339	258	56	497	228	269	34	606	351	255	62
6 Oct	T	Low	490	266	224	51	329	149	180	19	617	355	262	65
	T	High	497	263	234	49	317	139	178	19	623	356	266	69
	A	Low	517	291	227	52	272	126	146	18	674	404	270	78
	A	High	521	295	226	62	303	134	168	18	677	407	271	78
	K	Low	526	298	228	50	406	185	221	24	615	368	248	64
	K	High	538	308	229	56	380	173	206	24	644	390	254	64
27 Oct	T	Low	540	286	255	50	288	125	163	17	702	401	301	78
	T	High	556	302	254	54	290	118	171	18	697	416	281	79
	A	Low	554	308	246	57	303	129	175	17	754	458	296	81
	A	High	616	344	272	59	278	114	164	18	758	457	301	81
	K	Low	584	328	256	58	289	123	166	21	714	437	278	69
	K	High	573	327	246	52	279	120	158	20	672	406	266	68
S.E.M.														
H (4 D.F.)			7·8	4·0	4·6	0·4	5·9	3·4	3·0	0·3	9·0	7·4	2·9	1·5
C (18 D.F.)			7·2	5·5	2·5	0·9	5·1	2·4	3·5	0·2	4·0	3·8	2·6	1·5
N (18 D.F.)			6·8	4·8	2·5	0·8	4·4	2·4	2·7	0·2	4·3	3·8	2·1	1·1
H × C × N (18 D.F.)			20·4	14·4	7·4	2·4	13·2	7·1	8·2	0·6	13·0	11·3	6·2	3·4

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.
† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

rate, while the DDM content, starch, hemicellulose and ash concentrations of whole-crop, cob or stover silages were also unaffected ($P>0·05$) by N application rate (Tables 4 and 5).

Later harvesting did not affect ($P>0·05$) the DDM content of whole-crop silages, while the DDM content of cob silages from crops harvested on 15 September and stover silages from crops harvested on 27 October were lower ($P<0·05$) than on other harvest dates. The starch content was lower ($P<0·001$) and the WSC, NDF, ADF, hemicellulose, CP and ash concentrations were higher for whole-crop and cob silages produced from crops harvested on 15 September compared with later harvest dates. Stover silages produced from crops harvested on 27 October had higher ($P<0·05$) NDF, ADF and hemicellulose concentrations and a lower ($P<0·05$) CP concentration compared with earlier harvest dates.

Whole-crop and stover silages produced from Tassilo had a higher ($P<0·05$) DDM content compared with the other cultivars, while stover silages produced from Tassilo also had lower ($P<0·05$) NDF and ADF concentrations and a higher ($P<0·01$) CP concentration than the other cultivars. Whole-crop and cob silages from KXA 7211 had a lower starch concentration ($P<0·001$) and higher ($P<0·05$) NDF, ADF and hemicellulose concentrations compared with the other cultivars, while cob silages produced from KXA 7211 and harvested on 15 September or 6 October also had a higher ($P<0·001$) ash concentration than the other cultivars. Cob silages produced from Andante had a higher ($P<0·001$) starch concentration and lower ($P<0·05$) NDF, ADF, hemicellulose and CP concentrations than the other cultivars.

Change in chemical composition (non-fermentation) during ensilage

The changes in chemical composition of whole-crop and stover due to ensiling were unaffected ($P>0·05$) by N application rate. The increase in DM, NDF and ADF concentrations and the decrease in DDM content and ash content due to ensiling were greater ($P<0·05$) for cobs produced from high N application rate crops than low N application rate crops (Tables 6 and 7).

The extent of change in DM concentration due to ensiling of whole-crop and cob was unaffected ($P>0·05$) by harvest date, while the reduction of DM concentration due to ensiling of stover was greater ($P<0·05$) for crops harvested on 15 September than later harvest dates. For whole-crop, the increase in NDF, ADF, CP and ash concentrations and the decrease in the WSC concentration due to ensiling was greater ($P<0·01$) for crops harvested on 15 September compared with later harvest dates, while the increase in DDM content and decrease in hemicellulose concentration due to ensiling was of a greater ($P<0·01$) magnitude for crops harvested on 27 October than at earlier harvest dates. The increase in starch, NDF, ADF, hemicellulose and CP concentrations and the decrease in WSC concentration due to ensiling of cobs was greater ($P<0·05$) for crops harvested on 15 September compared with 27 October. The increase in NDF, hemicellulose, CP and ash concentrations and the decrease in the WSC concentration due to ensiling of stover were lower ($P<0·05$) for crops harvested on 27 October compared with earlier harvest dates, while the increase in ADF concentration was greater ($P<0·05$) on 27 October compared with earlier harvest dates.

The increases in NDF and ADF and decrease in WSC, hemicellulose and DDM concentrations due to ensiling were greater ($P<0·05$) for whole-crop produced from KXA 7211, compared with Andante. The increases in NDF, ADF and hemicellulose concentrations, and the decreases in WSC concentration and DDM content due to ensiling, were greater ($P<0·05$) for cobs produced from KXA 7211 than Andante. The increases in ADF and CP concentrations and the decrease in WSC content due to ensiling were lower ($P<0·05$) for stover produced from Andante than the other cultivars.

Fermentation products

No fermentation product concentrations of whole-crop and cob silages were affected by N application rate, with the exception of a higher ($P>0·001$) propionic acid concentration for cob silages produced from crops harvested from high N application rate plots on 15 September (Tables 8 and 9). Stover silages produced from crops grown on high N application rate plots had a higher ($P<0·05$) ammonia-N concentration and pH than crops grown on low N application rate plots.

The total fermentation products (TFP) of whole-crop, cob and stover silages decreased ($P<0·05$) with later harvesting. The lactic acid concentration of cob and stover silages was unaffected ($P>0·05$) by harvest date, while whole-crop silages had a lower ($P<0·01$) lactic acid concentration when produced from crops harvested on 15 September compared with later

Table 4. *DM concentration (g/kg), DDM (g/kg), WSC, starch and CP concentrations (g/kg DM) of forage maize whole-crop, cob and stover silages – harvest date, cultivar and N application rate effects*

			Whole-crop					Cob					Stover			
Harvest (H)	C*	N†	DM	DDM	WSC	Starch	CP	DM	DDM	WSC	Starch	CP	DM	DDM	WSC	CP
15 Sep	T	Low	200	709	22	124	108	294	727	3	258	96	173	643	12	94
	T	High	188	712	28	75	120	287	725	3	208	98	174	650	13	102
	A	Low	216	664	21	86	101	306	746	6	316	96	190	620	11	89
	A	High	213	676	23	94	108	318	739	3	296	91	200	613	11	96
	K	Low	188	656	22	16	110	165	817	3	30	132	191	617	14	85
	K	High	193	659	23	12	104	185	792	5	52	122	187	628	12	85
6 Oct	T	Low	242	750	2	259	86	432	835	0	511	85	172	620	11	74
	T	High	226	739	3	206	83	418	822	0	518	89	161	693	10	84
	A	Low	255	734	1	279	90	465	844	0	586	79	175	589	10	74
	A	High	240	692	2	217	82	458	816	3	578	82	177	630	9	72
	K	Low	218	712	4	117	92	314	827	0	344	98	180	631	12	77
	K	High	217	705	5	133	88	322	803	0	354	95	192	585	12	72
27 Oct	T	Low	253	718	2	260	89	479	815	0	583	83	179	606	18	75
	T	High	253	712	1	235	93	477	819	0	563	88	186	593	15	78
	A	Low	253	659	2	199	87	508	805	0	619	79	206	544	17	59
	A	High	274	684	0	250	87	494	810	0	629	83	207	541	16	68
	K	Low	225	665	4	139	83	390	819	1	511	84	197	567	17	60
	K	High	235	681	1	149	85	404	817	1	489	85	201	551	16	66
S.E.M.																
H (4 D.F.)			4·4	12·7	3·2	8·6	1·8	3·3	8·7	0·6	8·4	0·6	1·7	13·1	0·7	1·7
C (18 D.F.)			1·9	5·3	0·6	8·7	1·9	2·6	4·5	0·5	8·0	0·8	2·3	15·2	0·2	1·6
N (18 D.F.)			2·6	4·6	0·6	8·0	1·5	2·5	3·6	0·4	6·0	0·7	1·2	8·8	0·2	1·3
H × C × N (18 D.F.)			7·7	13·0	1·9	24·1	4·6	7·4	10·7	1·1	17·9	2·1	3·7	26·3	0·7	3·9

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.

† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

Table 5. *Structural carbohydrate and ash concentrations (g/kg) of forage maize whole-crop, cob and stover silages – harvest date, cultivar and N effects*

			Whole-crop				Cob				Stover			
Harvest (H)	C*	N†	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash
15 Sep	T	Low	597	346	251	63	557	277	280	20	697	418	279	80
	T	High	608	357	251	68	604	297	306	21	659	396	263	79
	A	Low	621	380	241	67	528	260	268	21	705	428	278	81
	A	High	591	359	233	75	541	271	270	20	685	421	264	82
	K	Low	693	425	267	70	706	335	371	37	699	429	270	82
	K	High	685	424	262	76	691	339	352	32	725	447	278	78
6 Oct	T	Low	516	293	223	55	297	143	155	16	722	443	279	85
	T	High	534	312	221	60	318	143	175	16	721	438	283	82
	A	Low	489	280	209	57	265	125	141	16	726	449	277	88
	A	High	548	332	216	63	282	126	155	15	748	468	280	87
	K	Low	582	347	235	62	464	222	242	22	717	436	281	82
	K	High	560	330	230	57	474	225	248	20	706	441	265	71
27 Oct	T	Low	509	285	224	53	239	102	137	16	714	427	287	82
	T	High	532	292	239	58	276	116	160	16	709	425	283	81
	A	Low	559	325	234	64	226	97	129	16	778	472	306	92
	A	High	530	302	229	55	232	103	129	17	761	465	296	88
	K	Low	581	347	233	55	291	126	165	18	753	474	280	68
	K	High	572	346	226	54	285	141	144	17	757	479	278	74
S.E.M.														
H (4 D.F.)			9·7	6·3	3·9	1·6	4·3	2·7	2·7	0·5	2·3	2·0	2·6	2·1
C (18 D.F.)			8·7	5·5	3·6	1·3	6·0	3·5	3·3	0·5	5·8	5·1	2·6	1·2
N (18 D.F.)			6·3	4·7	2·0	1·1	4·4	2·6	2·2	0·4	5·1	3·8	2·2	1·0
H × C × N (18 D.F.)			18·8	14·0	6·0	2·9	13·2	7·9	6·5	1·1	15·2	11·3	6·6	2·9

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.
† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

Table 6. *Absolute changes (silage-fresh crop) in DM concentration (g/kg), DDM (g/kg), non-structural carbohydrate and CP concentration (g/kg DM) of forage maize whole-crop, cob and stover silages – harvest date, cultivar and N application rate effects*

			Whole-crop					Cob					Stover			
Harvest (H)	C*	N†	DM	DDM	WSC	Starch	CP	DM	DDM	WSC	Starch	CP	DM	DDM	WSC	CP
15 Sep	T	Low	1	–46	–154	38	28	22	–34	–114	58	5	–21	–63	–185	24
	T	High	–4	–38	–193	16	36	42	–63	–126	27	3	–26	–73	–189	25
	A	Low	–1	–23	–134	14	21	50	–39	–91	75	–1	–19	21	–138	16
	A	High	–17	–48	–126	11	25	43	–22	–81	45	–1	–2	–43	–175	20
	K	Low	–7	–81	–178	–5	35	–27	–42	–165	5	19	–11	–61	–195	24
	K	High	–4	–26	–162	–6	29	29	–61	–172	9	7	–10	–55	–169	15
6 Oct	T	Low	27	–16	–148	67	16	41	40	–112	64	2	–4	–62	–166	17
	T	High	6	–26	–134	–8	7	27	11	–106	63	–1	–10	34	–157	14
	A	Low	9	14	–107	72	21	25	58	–75	38	1	–1	–10	–68	5
	A	High	19	–13	–149	29	6	29	46	–70	42	–2	–9	–41	–89	3
	K	Low	10	–43	–217	21	22	47	27	–157	65	5	–9	–27	–178	21
	K	High	10	–25	–219	60	17	74	1	–144	63	0	15	–60	–140	14
27 Oct	T	Low	10	28	–39	1	16	28	22	–36	4	–2	2	–21	–24	5
	T	High	17	13	–51	14	18	24	20	–40	–5	–1	18	–59	–38	8
	A	Low	–15	47	–31	–52	20	29	61	–26	5	0	3	–31	–6	0
	A	High	16	40	–36	71	15	11	28	–29	16	–1	3	–23	–10	–2
	K	Low	–2	–11	–118	18	14	40	2	–87	19	–4	15	–47	–61	5
	K	High	–2	1	–101	–1	12	53	–6	–92	–10	–6	2	–64	–85	3
S.E.M.																
H (4 D.F.)			3·9	7·4	18·0	5·6	1·9	5·5	8·3	1·9	6·0	0·8	2·6	15·5	15·7	1·5
C (18 D.F.)			4·2	9·3	5·6	13·4	2·4	3·1	5·9	1·9	7·4	0·9	3·6	11·0	7·3	1·6
N (18 D.F.)			3·4	7·4	4·5	11·0	1·9	2·6	4·8	1·5	6·1	0·7	3·0	8·8	5·9	1·3
H × C × N (18 D.F.)			10·3	21·2	13·6	32·9	5·8	7·7	14·5	4·6	18·2	2·2	8·9	25·0	17·8	4·0

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.

† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

Table 7. *Absolute changes (silage – fresh crop) in the structural carbohydrate and ash concentrations (g/kg DM) of maize whole-crop, cob and stover silages – harvest date, cultivar and N application rate effects*

			Whole-crop				Cob				Stover			
Harvest (H)	C*	N†	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash	NDF	ADF	Hemi	Ash
15 Sep	T	Low	83	72	11	14	63	47	15	–3	117	90	27	22
	T	High	82	78	3	20	117	67	50	–3	90	86	4	20
	A	Low	52	57	–4	12	81	47	33	–3	80	58	22	13
	A	High	21	51	–29	20	67	40	27	–4	78	63	15	14
	K	Low	120	98	22	13	208	107	101	3	93	78	15	22
	K	High	88	84	4	20	194	111	83	–2	119	96	22	13
6 Oct	T	Low	26	27	–2	4	–31	–6	–25	–3	104	88	16	20
	T	High	37	50	–13	11	2	5	–3	–3	98	82	16	13
	A	Low	–28	–11	–18	5	–7	–1	–6	–2	52	45	7	10
	A	High	27	37	–10	1	–21	–8	–13	–3	71	61	10	9
	K	Low	56	49	7	11	58	38	21	–3	102	69	33	18
	K	High	23	22	0	1	94	52	42	–4	62	51	11	7
27 Oct	T	Low	–32	–1	–31	3	–49	–22	–27	–1	12	25	–14	4
	T	High	–25	–10	–15	5	–13	–3	–11	–1	11	9	3	1
	A	Low	5	17	–12	3	–78	–32	–46	0	24	14	10	11
	A	High	–86	–43	–43	–4	–46	–11	–34	–1	3	9	–6	8
	K	Low	–3	19	–22	–2	2	3	–1	–3	39	37	2	1
	K	High	–1	19	–20	2	7	21	–14	–3	85	73	12	6
S.E.M.														
H (4 D.F.)			9·7	7·4	3·5	1·5	5·3	4·2	3·5	0·6	9·3	8·3	3·0	1·3
C (18 D.F.)			12·5	9·3	4·0	1·2	6·2	3·6	3·8	0·4	7·4	5·6	3·2	1·5
N (18 D.F.)			10·2	7·6	3·3	1·0	5·0	3·0	3·1	0·3	6·0	4·6	2·6	1·3
H × C × N (18 D.F.)			30·6	22·8	9·8	3·0	15·1	8·9	9·2	1·0	18·1	13·8	7·9	3·8

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.
† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

Table 8. *Individual fermentation product concentrations (g/kg DM) of whole-crop maize, cob and stover due to ensiling – harvest date, cultivar and N application rate effects*

			Whole-crop					Cob					Stover				
Harvest (H)	C*	N†	LA	AA	Eth	PA	BA	LA	AA	Eth	PA	BA	LA	AA	Eth	PA	BA
15 Sep	T	Low	23	84	72	8·1	0·46	24	33	29	1·1	0·10	31	73	66	6·0	0·75
	T	High	26	94	88	9·3	0·31	22	29	26	1·3	0·11	52	72	70	5·0	0·51
	A	Low	35	78	58	9·3	1·53	12	30	24	1·2	0·34	33	72	61	5·4	1·20
	A	High	38	80	60	9·6	1·40	18	32	27	1·3	0·09	82	68	56	5·0	1·00
	K	Low	35	110	84	13·1	0·52	29	62	59	1·9	0·27	64	66	63	4·7	0·71
	K	High	33	96	81	11·3	0·75	26	50	37	3·8	0·78	47	69	65	4·5	0·73
6 Oct	T	Low	50	71	49	8·9	0·63	37	18	18	0·7	0·91	23	70	56	5·0	0·43
	T	High	72	63	56	7·7	0·62	31	18	21	0·8	0·67	33	68	53	8·8	1·17
	A	Low	58	45	35	6·5	1·24	10	16	15	0·8	0·66	34	64	47	5·6	0·89
	A	High	38	60	39	7·5	0·90	24	15	13	0·7	0·47	13	63	47	5·3	0·94
	K	Low	104	46	56	3·9	0·58	16	37	43	1·3	0·40	60	70	61	5·9	0·82
	K	High	124	44	43	4·5	0·44	36	28	34	1·1	0·20	113	48	44	4·1	0·78
27 Oct	T	Low	75	31	22	3·9	0·72	31	9	6	0·4	0·38	64	54	36	6·0	1·53
	T	High	79	34	22	4·0	0·41	25	8	6	0·5	0·38	93	43	25	4·7	1·12
	A	Low	88	28	16	4·0	1·83	23	7	5	0·5	0·70	1	58	41	8·7	7·08
	A	High	76	29	18	4·4	1·43	11	10	6	0·8	1·67	6	54	36	6·9	5·90
	K	Low	109	27	26	2·4	0·91	40	11	10	0·6	0·40	86	42	30	3·5	1·26
	K	High	99	30	26	2·3	0·95	42	11	13	0·6	0·73	71	44	27	4·3	3·71
S.E.M.																	
H (4 D.F.)			4·7	3·5	4·1	0·40	0·109	2·8	1·7	1·7	0·14	0·083	3·3	3·3	2·9	0·22	0·122
C (18 D.F.)			4·9	1·9	1·6	0·58	0·317	2·6	1·6	1·8	0·06	0·125	6·9	2·2	2·1	0·47	0·476
N (18 D.F.)			4·0	1·5	1·3	0·48	0·258	2·0	1·5	1·3	0·04	0·094	5·6	1·8	1·7	0·38	0·389
H × C × N (18 D.F.)			12·1	4·5	3·9	1·43	0·775	6·0	3·7	4·0	0·13	0·283	16·8	5·5	5·2	1·14	1·167

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.
† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.
LA, lactic acid; AA, acetic acid; Eth, ethanol; PA, propionic acid; BA, butyric acid.

Table 9. *pH, ammonia–N (NH_3–N, g/kg N) concentration, TFP (g/kg DM) and proportion of lactic acid in TFP (g lactic acid/ kg TFP) of whole-crop maize, cob and stover silages – harvest date, cultivar and N application rate effects*

			Whole-crop				Cob				Stover			
Harvest (H)	C*	N†	pH	NH_3-N	TFP	LA/TFP	pH	NH_3-N	TFP	LA/TFP	pH	NH_3-N	TFP	LA/TFP
15 Sep	T	Low	4·1	74	187	117	3·9	33	87	270	4·0	56	177	186
	T	High	4·0	56	218	120	3·9	59	78	283	3·8	38	199	239
	A	Low	4·0	64	182	197	4·2	84	67	180	4·1	54	172	195
	A	High	4·0	69	188	206	4·2	66	78	226	3·9	60	211	377
	K	Low	4·0	86	243	146	4·1	67	152	191	4·0	76	199	300
	K	High	4·1	78	222	143	4·1	73	117	225	4·0	57	185	246
6 Oct	T	Low	3·7	66	180	277	3·7	67	74	490	4·2	62	154	151
	T	High	3·8	82	199	337	3·7	74	71	439	4·1	52	165	204
	A	Low	4·0	78	146	395	4·0	81	42	230	4·4	42	152	225
	A	High	4·1	89	146	265	3·8	95	53	449	4·4	55	129	98
	K	Low	3·5	44	210	497	4·1	96	97	159	3·9	59	197	304
	K	High	3·4	101	216	537	3·8	122	99	358	3·5	48	210	535
27 Oct	T	Low	3·8	64	133	565	4·0	94	47	617	4·1	52	161	393
	T	High	3·8	66	140	558	3·9	69	39	620	3·9	33	167	561
	A	Low	3·8	62	137	648	3·9	113	36	607	4·9	47	116	10
	A	High	3·8	65	129	591	4·2	116	30	368	4·5	27	108	61
	K	Low	3·6	49	165	668	3·8	254	62	648	3·9	41	163	522
	K	High	3·6	46	158	625	3·9	176	67	624	4·0	52	150	420
S.E.M.														
H (4 D.F.)			0·04	6·7	6·3	20·9	0·03	5·6	4·1	29·9	0·06	2·9	3·8	20·4
C (18 D.F.)			0·04	4·1	5·2	16·3	0·04	6·7	3·9	22·2	0·06	3·1	5·1	31·1
N (18 D.F.)			0·03	3·4	4·3	13·3	0·03	5·5	3·0	20·9	0·05	2·3	4·2	25·4
H × C × N (18 D.F.)			0·09	10·1	12·9	39·8	0·09	16·5	9·0	50·3	0·15	7·0	12·6	76·3

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.

† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

harvest dates. Acetic acid and ethanol concentrations of whole-crop, cob and stover silages produced from crops harvested on 27 October were lower ($P<0·05$) than on earlier harvest dates. Propionic acid was higher ($P<0·01$) for whole-crop and cob silages produced from crops harvested on 15 September compared with on 27 October, while the propionic acid concentration of stover silage was unaffected ($P>0·05$) by harvest date. The concentration of butyric acid was lower ($P<0·001$) for cob and stover silages, respectively, produced from crops harvested on 15 September compared with on 27 October, while butyric acid production in whole-crop silages was unaffected ($P>0·05$) by harvest date. The proportion of lactic acid in the TFP of whole-crop and cob silages increased ($P<0·05$) with later harvesting, and it was unaffected ($P>0·05$) by harvest date for stover silages. The ammonia-N concentration of cob silage increased ($P<0·05$) with later harvesting, while the ammonia-N concentration of whole-crop and stover silages was unaffected ($P>0·05$) by harvest date. The pH of whole-crop and cob silages produced from crops harvested on 15 September was higher ($P<0·05$) compared with later harvest dates, while stover silage produced from crops harvested on 15 September had a lower ($P<0·05$) pH than on later harvest dates.

The TFP concentration of whole-crop, cob and stover silages produced from KXA 7211 was higher ($P<0·01$) than Andante. The concentrations of lactic acid were higher ($P<0·05$) in whole-crop and stover silages produced from KXA 7211, compared with the other cultivars. The concentrations of acetic acid, ethanol and propionic acid were higher ($P<0·001$) for cob silages produced from KXA 7211 compared with the other cultivars, although acetic acid concentrations of cob silages produced from crops harvested on 27 October were unaffected ($P>0·05$) by cultivar. Cob and stover silages produced from the Andante cultivar had higher ($P<0·05$) butyric acid concentrations than other cultivars, while the butyric acid concentration of whole-crop silages was unaffected ($P>0·05$) by cultivar. The proportion of lactic acid in the TFP of whole-crop and stover silages was higher ($P>0·05$) for KXA 7211 compared with the other cultivars, while the proportion which lactic acid contributed to TFP in cob silages was higher ($P>0·01$) for Tassilo than the other cultivars. Cob silages produced from KXA 7211 had higher ($P<0·01$) ammonia-N concentrations than the other cultivars, while the ammonia-N concentration of whole-crop and stover silages were unaffected by cultivar. The pH of whole-crop and stover silages produced from KXA 7211 was lower ($P>0·001$) than Andante, while the pH of cob silages produced from Tassilo was lower ($P>0·05$) than other cultivars.

DM recovery and aerobic stability

Higher N application did not affect ($P>0·05$) DM recovery, effluent production, aerobic stability or aerobic deterioration of whole-crop or cob silages (Table 10). Stover silages produced from cultivars grown under the high N application rates had lower yeast numbers ($P<0·05$) than low application rate plots.

Harvest date did not affect ($P>0·05$) DM recovery, aerobic stability or deterioration of whole-crop maize silages. Cob silages harvested on 15 September had a lower ($P<0·05$) DM recovery and higher ($P<0·01$) effluent production than on later harvest dates, while cob silages produced from crops harvested on 27 October had a higher ($P<0·05$) accumulated temperature rise after 120 h and underwent a 2 °C rise above ambient temperature in less time ($P<0·05$) than earlier harvest dates. Stover silages harvested on 27 October had higher ($P<0·01$) DM recovery than on earlier harvest dates.

Whole-crop silages produced from KXA 7211 had lower ($P<0·01$) hours to a 2 °C rise above ambient temperature and accumulated temperature rise after 120 h, compared with the other cultivars, while cob silages from KXA 7211 had a lower ($P<0·001$) DM recovery and ($P<0·001$) higher effluent production than the other cultivars. Stover silages from Tassilo had lower ($P<0·001$) hours to a 2 °C rise above ambient temperature and higher ($P<0·05$) accumulated temperature rise after 120 h than the other cultivars.

DISCUSSION

Yield, agronomy and pre-ensilage chemical composition

The mean (S.D.) whole-crop DM yield of 10·6 (1·42) t/ha and DM concentration of 223 (21·9) g/kg in the present study was low compared with the mean values (15·0–19·8 t/ha; 300–390 g/kg) reported for crops grown under plastic mulch in Ireland by Easson & Fearnehough (2000), Keane (2002), Keane *et al.* (2003), Little *et al.* (2008) and Farrell & Gilliland (2011). However, the low average yield is more

Table 10. *DM recovery (DMR; g silage/kg herbage), LAB and yeast counts Log$_{10}$(colony forming units/g herbage) and aerobic stability (ITR; interval (hours) until a temperature rise >2 °C) and deterioration (ACT; accumulated temperature (°C) rise after 120 h exposure to air) of whole-crop, cob and stover silages – harvest date, cultivar and N application rate effects*

			Whole-crop					Cob					Stover				
Harvest (H)	C*	N†	DMR	LAB	Yeast	ITR	ACT	DMR	LAB	Yeast	ITR	ACT	DMR	LAB	Yeast	ITR	ACT
15 Sep	T	Low	903	8·04	1·23	192	0·0	809	7·37	ND	192	1	845	7·22	1·16	192	1
	T	High	849	7·98	1·10	192	1·4	869	7·63	1·6	167	1	812	7·11	1·00	192	1
	A	Low	924	8·26	1·86	173	1·2	881	7·98	2·7	170	1	863	7·70	3·53	192	0
	A	High	888	7·61	2·33	192	0·6	880	7·68	2·6	116	3	943	7·14	ND	192	0
	K	Low	848	7·60	2·49	169	0·8	674	6·80	1·2	177	1	881	7·21	2·46	185	1
	K	High	894	7·40	1·10	130	3·6	736	7·74	4·3	117	10	852	6·92	ND	192	0
6 Oct	T	Low	987	7·58	2·00	151	4·6	970	8·07	3·7	99	13	879	7·86	1·20	87	8
	T	High	936	7·91	1·00	165	1·8	940	7·65	2·4	122	3	832	8·00	ND	184	1
	A	Low	966	8·12	3·26	148	4·8	943	8·00	1·0	106	4	891	7·42	1·00	192	1
	A	High	935	7·89	1·23	181	1·0	965	7·93	2·8	164	1	850	7·90	1·00	192	0
	K	Low	920	7·68	1·86	145	5·4	821	7·75	1·5	192	3	842	7·80	2·00	192	0
	K	High	929	7·42	2·78	97	13·2	915	7·42	1·0	186	1	915	7·20	1·00	192	0
27 Oct	T	Low	985	7·57	1·16	154	2·4	987	7·63	2·8	89	16	984	7·88	ND	189	1
	T	High	993	7·84	2·33	192	0·2	1000	8·14	3·8	57	21	1000	7·77	1·20	190	1
	A	Low	931	7·68	ND	192	0·5	980	7·84	4·1	79	10	983	7·78	ND	192	1
	A	High	950	7·60	1·00	188	1·0	998	7·28	2·7	129	3	942	7·19	1·00	192	1
	K	Low	915	7·78	1·20	159	2·7	979	7·33	2·8	53	17	990	7·71	1·00	164	2
	K	High	908	7·37	1·10	101	10·7	985	7·57	4·2	54	24	914	7·80	ND	185	1
S.E.M.																	
H (4 D.F.)			15·9	0·049	0·714	17·8	1·86	23·8	0·111	0·312	5·5	1·3	10·3	0·089	0·280	3·1	0·3
C (18 D.F.)			14·7	0·114	0·441	12·6	1·40	12·2	0·110	0·516	10·0	2·2	14·6	0·094	0·377	4·2	0·5
N (18 D.F.)			12·0	0·079	0·301	7·1	0·68	10·2	0·111	0·338	5·5	1·1	11·9	0·106	0·260	1·8	0·4
H × C × N (18 D.F.)			36·0	0·238	0·902	21·4	2·03	27·6	0·333	1·015	16·5	3·4	35·3	0·317	0·779	5·5	1·1

* C = cultivar, T = Tassilo, A = Andante, K = KXA 7211.

† N = nitrogen input, Low = 33 kg N/ha, High = 168 kg N/ha.

similar to yields of 11·8 (1·71) t/ha obtained at the same site and reported in previous work by Lynch *et al.* (2010), and can be partially explained by lower temperatures during the growing season (2312 OHU) compared with temperatures reported by Easson & Fearnehough (2000; 2554 OHU) and Farrell & Gilliland (2011; 2814 OHU).

The absence of an effect of higher N application on the DM yield of either whole-crop or cob is in contrast with Muchow (1998), Cox & Cherney (2001) and Masoero *et al.* (2011), who reported increasing whole-crop and grain DM yield with increasing rates of N application. However, Sheaffer *et al.* (2006) reported that the positive response of maize whole-crop and grain DM yield to increased N application was quadratic, whereas the positive response of stover DM yield was linear and in accordance with the findings of the present study. Considering the combination of firstly the relatively high soil organic N content at the experimental site (8·3 g/kg at 50 mm depth; Travers 1999) and its likely partial mineralization while the maize crop was growing and, secondly the N provided by the cattle slurry (applied to both N application rate treatments), it is possible that much of N requirements of the crop (particularly of the cob) were met from these sources under the sub-optimal temperature conditions that prevailed. Under such circumstances the response of cob DM yield to the application of additional inorganic N might be expected to be small or absent. In addition, the relatively low temperature during the growing season may have restricted the growth of the plant thereby lowering its optimum N requirement and reducing the capacity of the crop to respond to increased N application.

The lack of an effect of the higher rate N application on the chemical composition of whole-crop, cob and stover, other than the effect on CP concentration, is in accord with Sheaffer *et al.* (2006), Lawrence *et al.* (2008) and Masoero *et al.* (2011).

The increase in cob DM yield with later harvesting was similar to the findings of Hunt *et al.* (1989) and Little *et al.* (2008) and reflected the increasing DM concentration of cobs during grain fill. The lack of an effect of harvest date on whole-crop DM yield was due to the increase in cob yield being counter-balanced by a decrease in stover DM yield. In addition, leaf senescence may have partially explained the lower DM yield of stover when crops were harvested at later harvest dates, while Phipps & Weller (1979) observed that the decrease in DM yield of maize stems harvested at later harvest dates was concurrent with the translocation of WSC from the stem to the grain during the reproductive development of the plant.

The main reason for the increase in whole-crop and cob DM concentration with advancing harvest date was the increase in the starch concentration of the cob during grain fill (Phipps & Weller 1979). The lower stover DM concentration of crops harvested on 6 October compared with other harvest dates is in contrast to previous studies by Russell (1986), Little *et al.* (2008) and Lynch *et al.* (2010), who reported increasing DM concentration of stover with later harvesting. This unexpected effect in the present study was probably influenced by high rainfall (21·2 mm) on the 6 October harvest date.

The lower DDM content of whole-crop and stover at later harvest dates reflects concurrent increases in NDF and ADF concentrations and decreases in CP and WSC concentrations. The absence of an effect of harvest date on the DDM content of cob may be explained by the effects of increasing starch concentration and decreasing NDF and ADF concentrations counter-balancing reductions in WSC and CP concentrations.

The higher whole crop DM yield for the later maturing cultivar KXA 7211 compared with the conventional cultivars appeared to be primarily due to its higher yield of stover DM. This is in accord with Little *et al.* (2008) and Lynch *et al.* (2010), who reported higher whole-crop DM yields despite lower cob proportions in the whole-crop for later maturing compared with earlier maturing cultivars.

The higher DM concentration of the whole-crop and cob produced from Andante on 15 September reflected the higher starch concentration of this earlier maturing cultivar. This agrees with the interaction which occurred between harvest date and cultivar in the present study, where a smaller subsequent increase in starch concentration and no further decrease in NDF or ADF concentration of Andante were observed between 6 October and 27 October.

The lower DDM content for whole-crop, cob and stover produced from Andante resulted from lower CP and WSC concentrations in the cob and higher NDF and ADF concentrations and the lower WSC concentration in the stover, when compared with the other cultivars. In addition, the more advanced maturity of cob starch from Andante may have reduced its DDM content, which would be in accord with Philippeau and Michalet-Doreau (1997) who reported decreasing ruminal starch degradation with increasing grain maturity.

Fermentation dynamics

Whole-crop maize typically encourages good preservation of silage due to adequate concentrations of fermentable substrate and low BC values compared with other common forages (Playne & McDonald 1966; Allen *et al.* 2003). The WSC concentrations of whole-crop maize in the present study, expressed on an aqueous phase basis for use as an index of forage ensilability (O'Kiely & Muck 1998), of 46, 46 and 20 g WSC/l aqueous phase for herbage harvested on 15 September, 6 October and 27 October, respectively, along with the range of low mean BC values (221–278 mEq/kg DM), suggest a forage readily capable of supporting an adequate lactic acid dominant fermentation. Similarly, cob (mean (s.d.); 44 (14·1) g WSC/l; 106–351 mEq/kg DM) and stover (30 (16·1) g WSC/l; 224–345 mEq/kg DM) were both readily ensilable due to low buffering capacities combined with adequate concentrations of WSC.

The mean (s.d.) value of 179 (35·0) g TFP/kg DM was higher and the 0·33 (0·225) g lactic acid/g TFP was lower for ensiled whole-crop silage than the range of values reported in previous work by Walsh *et al.* (2008*a*, *b*; 70–93 g TFP/kg DM, 0·61–0·66 g lactic acid/g TFP) and McGeough *et al.* (2009; 38–56 g TFP/kg DM, 0·80–0·95 g lactic acid/g TFP), with the higher initial DM concentrations of 300–315 g/kg (Walsh *et al.* 2008*a*, *b*) and 227–339 g/kg (McGeough *et al.* 2009) partially explaining the more restricted fermentation in these other studies.

The low proportion of lactic acid in TFP compared with previous studies indicates a predominantly heterolactic fermentation. As the pre-ensiled herbage had a low BC and adequate fermentable substrate to facilitate a mainly lactic acid fermentation, it is likely that the increased heterolactic fermentation was due to differences in the indigenous bacterial composition rather than differences in the pre-ensiling chemical composition of the herbage. Undesirable enterobacterial and clostridial activity was probably minimal, as evidenced by low butyric acid and NH_3-N concentrations. In addition, the low BC of the forages probably facilitated a rapid decline in pH at the early stage of the ensilage process, and this restricted enterobacterial and clostridial activity. Yeast populations of silages in the present study were generally low, reflecting high concentrations of undissociated acetic acid (Muck 2010). Therefore, the unexpected fermentation dynamics observed in the present study were likely to be a result of differences in the LAB population. A possible explanation for the lower than expected contribution of lactic acid to TFP at the end of the ensiling period may be the utilization of lactic acid during ensilage as a substrate by some LAB, such as *Lactobacillus buchneri,* and the consequent production of other fermentation products. For example, Driehuis *et al.* (1999) reported that maize silages inoculated with *L. buchneri* had increasingly lower lactic acid proportions of TFP as the ensiling period was increased up to 200 days. Furthermore, Oude Elferink *et al.* (2001) reported that *L. buchneri* converted lactic acid to acetic acid, 1,2-propanediol and ethanol in liquid culture. In addition, other common silage microflora such as some *Propionibacterium* spp. (Pahlow *et al.* 2003) and *L. plantarum* (Lindgren *et al.* 1990) have been reported to ferment lactic acid under certain conditions.

The absence of an effect of N application rate on the fermentation dynamics of whole-crop, cob or stover silages is in accord with the lack of an effect on the pre-ensiled chemical composition.

The restriction of fermentation with later harvesting, as evidenced by the decrease of TFP concentration, reflected the simultaneous increase in DM concentration, and this agrees with Wilkinson & Phipps (1979), Johnson *et al.* (2002) and Filya (2004). This decrease in TFP concentration primarily resulted from decreases in the concentrations of acetic acid and ethanol in the silages. However, the increase in the lactic acid concentration of whole-crop and cob silages with later harvesting and the subsequent increase in the contribution of lactic acid to TFP disagrees with these previous studies, which reported decreasing lactic acid concentrations with later harvesting. The increased homolactic character of the fermentation with later harvesting in the present study may reflect a reduced activity of lactic acid utilizing micro-organisms in later harvested crops.

The reduced acetic acid and ethanol concentrations in stover silages harvested at later harvest dates agrees with Russell (1986). However, the simultaneous increase in stover DM concentration and reduction in lactic acid concentration observed by Russell (1986) were not observed in the present study.

The more extensive fermentation recorded with whole-crop and cob silages produced from KXA 7211 than for the other cultivars was due to the combined effects of their lower initial DM concentration, higher WSC concentration and higher BC. This is in accord with Lynch *et al.* (2010), who reported higher TFP concentrations for later compared with earlier maturing cultivars.

Post-ensilage chemical composition (non-fermentation)

The smaller reduction in cob DDM content during the ensilage of crops harvested on 15 September for the low rather than the high N application rate, and the corresponding larger increase in cob DDM content during the ensilage of crops harvested on the remaining two harvest dates when the rate of N application was low, is explained by the smaller increase in ADF concentration during the ensilage of cobs from low N application rate plots.

The effects of harvest date on the chemical composition of whole-crop, cob and stover silages were generally similar to the effects on the pre-ensiled herbage. Most of the WSC present in pre-ensiled whole-crop and cob was fermented during the ensiling process and thus harvest date had little effect on silage WSC concentration. Harvesting whole-crop and cob on 28 October rather than 15 September resulted in greater increases in DDM content during ensilage due primarily to a smaller concurrent reduction in the WSC concentration and a higher concentration of starch. The latter is typically not utilized as a substrate by LAB during the production of well-preserved silages (Woolford 1984).

Losses due to ensilage and aerobic exposure

The values for the indices of aerobic stability (97–192 h for silage temperature to increase more than 2 °C above ambient temperature) and aerobic deterioration (1–13 °C accumulated temperature rise during 120 h exposure to air) in the present study indicate that these whole-crop silages were more aerobically stable than the maize silages reported by McGeough *et al.* (2009; 13–18 h of aerobic stability, 84–97 °C accumulated temperature rise) and Walsh *et al.* (2008*a*, *b*; 38–39 h of aerobic stability, 53–70 °C accumulated temperature rise). The superior aerobic stability in the present study reflected the high concentration of acetic acid inhibiting yeast activity.

No N application rate effects were observed on the DM recovery or the aerobic stability of whole-crop, cob or stover silages due to the lack of effect of N application rate on the fermentation dynamics or chemical composition of these silages.

The effects of harvest date or cultivar on the aerobic deterioration of whole-crop or stover silages were minimal and as the majority of these silages had a high acetic acid concentration and consequently low yeast populations, they were all aerobically stable.

Cob silages made from crops harvested on 15 September rather than later harvest dates had a lower DM recovery. This was primarily due to increased effluent loss associated with their lower DM concentration (Hameleers *et al.* 1999), but also partially due to increased gas production resulting from the more extensive and more heterolactic fermentation in the cob silages. Cob silages produced from crops harvested on 15 September had better aerobic stability characteristics than those made from crops harvested on 27 October, corresponding to their higher acetic acid and propionic acid concentrations which inhibit the growth of yeast (Woolford 1975), the main organisms involved in the initiation of aerobic deterioration (Danner *et al.* 2003).

Cob silage produced from cvar KXA 7211 had a lower DM recovery than for other cultivars, primarily due to its lower DM concentration at ensiling resulting in increased effluent production.

In conclusion, increasing the N application rate generally did not confer an advantage to the yield or nutritive value of whole-crop maize grown in marginal climatic conditions or to its individual cob and stover components. The higher N application rate therefore did not impact on the ensiling characteristics or aerobic stability of silages produced from these herbages. This suggests that N fertilizer application rate should be based on site-specific estimations, rather than the maximum application allowed by legislation, in order to reduce un-rewarded expensive inputs in the total maize silage production system. The effects of harvest date on cob and stover were generally contrasting, with later harvesting resulting in a higher yield and nutritive value of cob, and a lower yield and nutritive value of stover. Despite higher whole-crop DM yields, the later maturing cultivar KXA 7211 did not improve the yields or nutritive value of cob silage and also resulted in increased cob DM losses during the ensiling process. Therefore, fermentation losses during ensilage can influence the choice of optimum cultivar and date for crop harvest in a maize silage production system, and future studies investigating the effects of crop management factors on forage maize should discuss the potential impact of such factors on the subsequent ensilage process. In addition, the present study indicated that the contrasting chemical composition and fermentation profiles of the cob and stover, and their relative proportions in the total plant influence the nutritive value and conservation characteristics of whole-crop maize silage.

Funding for this study was provided under the National Development Plan through the Research Stimulus fund administered by the Department of Agriculture, Fisheries and Food (RSF 07 501). The provision of maize seed by Seed Technology Ltd., Ballymountain, Ferrybank, Waterford, Ireland, the input into crop production and ensilage by B. Weldon and Grange farm staff and the chemical analyses undertaken by Grange laboratory staff is also acknowledged.

REFERENCES

Allen, M. S., Coors, J. G. & Roth, G. W. (2003). Corn silage. In *Silage Science and Technology* (Eds D. R. Buxton, R. E. Muck & J. H. Harrison), pp. 547–608. Agronomy Monograph No. 42. Madison, WI: American Society of Agronomy.

ANKOM (2006*a*). *Acid Detergent Fiber in Feeds Filter Bag Technique*. Ankom Technology Method 8. Macedon, NY: Ankom Technology.

ANKOM (2006*b*). *Neutral Detergent Fiber in Feeds Filter Bag Technique*. Ankom Technology Method 6. Macedon, NY: Ankom Technology.

AOAC (Association of Official Analytical Chemists) (1990). *Official Methods of Analysis*. First supplement to the 15th edition, method 990–03. Arlington, VA: AOAC.

Cox, W. J. & Cherney, D. J. R. (2001). Row spacing, plant density, and nitrogen effects on corn silage. *Agronomy Journal* **93**, 597–602.

Crowley, J. G. (1998). *Improving the Yield and Quality of Forage Maize*. End of Project Report 4162. Oak Park, Carlow, Republic of Ireland: Teagasc.

Danner, H., Holzer, M., Mayrhuber, E. & Braun, R. (2003). Acetic acid increases stability of silage under aerobic conditions. *Applied and Environmental Microbiology* **69**, 562–567.

Driehuis, F., Oude Elferink, S. J. W. H. & Spoelstra, S. F. (1999). Anaerobic lactic acid degradation during ensilage of whole crop maize inoculated with *lactobacillus buchneri* inhibits yeast growth and improves aerobic stability. *Journal of Applied Microbiology* **87**, 583–594.

Easson, D. L. & Fearnehough, W. (2000). Effects of plastic mulch, sowing date and cultivar on the yield and maturity of forage maize grown under marginal climatic conditions in Northern Ireland. *Grass and Forage Science* **55**, 221–231.

Farrell, A. D. & Gilliland, T. J. (2011). Yield and quality of forage maize grown under marginal climatic conditions in Northern Ireland. *Grass and Forage Science* **66**, 214–223.

Filya, I. (2004). Nutritive value and aerobic stability of whole crop maize silage harvested at four stages of maturity. *Animal Feed Science and Technology* **116**, 141–150.

Finch, T. F., Gardiner, M. J., Comey, A. & Radford, T. (1983). *Soils of Co. Meath*. Dublin, Republic of Ireland: An Foras Taúntais.

Finneran, E., Crosson, P., O'Kiely, P., Shalloo, L., Forristal, D. & Wallace, M. (2012). Stochastic simulation of the cost of home-produced feeds for ruminant livestock systems. *Journal of Agricultural Science, Cambridge* **150**, 123–139.

Fitzgerald, D. A. & Fitzgerald, D. L. (2004). Meteorological measurements. In *Climate, Weather and Irish Agriculture* (Eds T. Keane & J. F. Collins), pp. 9–24. Dublin: Agmet.

Fitzgerald, J. J. & Murphy, J. J. (1999). A comparison of low starch maize silage and grass silage and the effect of concentrate supplementation of the forages or inclusion of maize grain with the maize silage on milk production by dairy cows. *Livestock Production Science* **57**, 95–111.

Hameleers, A., Leach, K. A., Offer, N. W. & Roberts, D. J. (1999). The effects of incorporating sugar beet pulp with forage maize at ensiling on silage fermentation and effluent output using drum silos. *Grass and Forage Science* **54**, 322–335.

Hunt, C. W., Kezar, W. & Vinande, R. (1989). Yield, chemical composition and ruminal fermentability of corn whole plant, ear, and stover as affected by maturity. *Journal of Production Agriculture* **2**, 357–361.

Johnson, L. M., Harrison, J. H., Davidson, D., Mahanna, W. C., Shinners, K. & Linder, D. (2002). Corn silage management: effects of maturity, inoculation, and mechanical processing on pack density and aerobic stability. *Journal of Dairy Science* **85**, 434–444.

Keady, T. W. J., Lively, F. O., Kilpatrick, D. J. & Moss, B. W. (2007). Effects of replacing grass silage with either maize or whole-crop wheat silages on the performance and meat quality of beef cattle offered two levels of concentrates. *Animal* **1**, 613–623.

Keane, G. P. (2002). Agronomic factors affecting the yield and quality of forage maize in Ireland: effect of sowing date and plastic film treatment. *Grass & Forage Science* **57**, 3–10.

Keane, G. P., Kelly, J., Lordan, S. & Kelly, K. (2003). Agronomic factors affecting the yield and quality of forage maize in Ireland: effect of plastic film system and seeding rate. *Grass and Forage Science* **58**, 362–371.

Lawrence, J. R., Ketterings, Q. M. & Cherney, J. H. (2008). Effect of nitrogen application on yield and quality of silage corn after forage legume-grass. *Agronomy Journal* **100**, 73–79.

Lindgren, S. E., Axelsson, L. T. & McFeeters, R. F. (1990). Anaerobic L-lactate degradation by *Lactobacillus plantarum*. *FEMS Microbiology Letters* **66**, 209–214.

Little, E. M., O'Kiely, P., Crowley, J. C. & Keane, G. P. (2008). Forage maize yield and maturity: interaction of harvest date, plastic mulch and cultivar (abstract). In Proceedings of the Agricultural Research Forum 2008, Tullamore, Co. Offaly, 12–13 March 2008, p. 118. Tullamore, Co. Offaly, Ireland: Agricultural Research Forum.

Lynch, J. P., O'Kiely, P. & Doyle, E. M. (2010). Yield and chemical composition of contrasting maize cultivars at sequential stages of maturity (poster presentation). In *Advances in Animal Biosciences: Proceedings of the British Society of Animal Science and the Agricultural Research Forum*, p. 322. Cambridge, UK: Cambridge University Press.

Masoero, F., Gallo, A., Zanfi, C., Giuberti, G. & Spanghero, M. (2011). Effect of nitrogen fertilization on chemical composition and rumen fermentation of different

parts of plants of three corn hybrids. *Animal Feed Science and Technology* **164**, 207–216.
McCleary, B. V., Solah, V. & Gibson, T. S. (1994). Quantitative measurement of total starch in cereal flours and products. *Journal of Cereal Science* **20**, 51–58.
McDonald, P., Henderson, A. R. & Heron, S. J. E. (1991). *The Biochemistry of Silage*. Marlow, Bucks, UK: Chalcombe Publications.
McGeough, E. J., O'Kiely, P., Foley, P. A., Hart, K. J., Boland, T. M. & Kenny, D. A. (2009). Methane emissions, feed intake and performance of finishing beef cattle offered maize silages harvested at four different stages of maturity. *Journal of Animal Science* **88**, 1479–1491.
Muchow, R. C. (1998). Nitrogen utilization efficiency in maize and grain sorghum. *Field Crops Research* **56**, 209–216.
Muck, R. E. (2010). Silage microbiology and its control through additives. *Revista Brasileira de Zootecnia* **39**, 183–191.
O'Kiely, P. & Moloney, A. P. (1995). Performance of beef cattle offered differing ratios of grass and maize silage. *Irish Journal of Agricultural and Food Research* **34**, 76.
O'Kiely, P. & Muck, R. E. (1998). Grass silage. In *Grass for Dairy Cattle* (Eds J. H. Cherney & D. J. R. Cherney), pp. 223–252. Wallingford, UK: CABI Publishing.
O'Kiely, P. & Wilson, R. K. (1991). Comparison of three silo types used to study in-silo processes. *Irish Journal of Agricultural Research* **30**, 53–60.
Oude Elferink, S. J. W. H., Krooneman, J., Gottschal, J. C., Spoelstra, S. F., Faber, F. & Driehuis, F. (2001). Anaerobic conversion of lactic acid to acetic acid and 1,2-propanediol by *Lactobacillus buchneri*. *Applied & Environmental Microbiology* **67**, 125–132.
Pahlow, G., Muck, R. E., Driehuis, F., Oude Elferink, S. J. W. H. & Spoelstra, S. F. (2003). Microbiology of ensiling. In *Silage Science and Technology* (Eds D. R. Buxton, R. E. Muck & J. H. Harrison), pp. 31–94. Madison, WI: American Society of Agronomy.
Philippeau, C. & Michalet-Doreau, B. (1997). Influence of genotype and stage of maturity of maize on rate of ruminal starch degradation. *Animal Feed Science and Technology* **68**, 25–35.
Phipps, R. H., Sutton, J. D., Beever, D. E. & Jones, A. K. (2000). The effect of crop maturity on the nutritional value of maize silage for lactating dairy cows. 3. Food intake and milk production. *British Society of Animal Science* **71**, 401–409.
Phipps, R. H. & Weller, R. F. (1979). The development of plant components and their effects on the composition of fresh and ensiled forage maize: 1. The accumulation of dry matter, chemical composition and nutritive value of fresh maize. *Journal of Agricultural Science, Cambridge* **92**, 471–483.
Playne, M. J. & McDonald, P. (1966). The buffering constituents of herbage and of silage. *Journal of the Science of Food and Agriculture*, **17**, 264–268.
Porter, M. G. & Murray, R. S. (2001). The volatility of components of grass silage on oven drying and the inter-relationship between dry-matter content estimated by different analytical methods. *Grass and Forage Science* **56**, 405–411.
Ranfft, K. (1973). Gas chromatography of short chain acids in ruminal fluids. *Archives Tierernahrung* **23**, 343–352.
Russell, J. R. (1986). Influence of harvest date on the nutritive value and ensiling characteristics of maize stover. *Animal Feed Science and Technology* **14**, 11–27.
SAS (2002). *SAS User's Guide, 9.1 edn*. Cary, NC: SAS Institute Inc.
Sheaffer, C. C., Halgerson, J. L. & Jung, H. G. (2006). Hybrid and N fertilization affect corn silage yield and quality. *Journal of Agronomy and Crop Science* **192**, 278–283.
Statutory Instruments 101 (2009). *European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2009*. Dublin: The Stationary Office.
Thomas, T. A. (1977). An automated procedure for the determination of soluble carbohydrates in herbage. *Journal of the Science of Food and Agriculture*, **28**, 639–642.
Tilley, J. M. A. & Terry, R. A. (1963). A two-stage technique for the in vitro digestion of forage crops. *Journal of the British Grassland Society*, **18**, 104–111.
Travers, G. (1999). *Nitrogen dynamics in grass and grass/clover swards grazed by beef cattle*. PhD thesis, Queen's University Belfast, Northern Ireland, UK.
Trindade, H., Coutinho, J., Jarvis, S. & Moreira, N. (2009). Effects of different rates and timing of application of nitrogen as slurry and mineral fertilizer on yield of herbage and nitrate-leaching potential of a maize/Italian ryegrass cropping system in north-west Portugal. *Grass and Forage Science*, **64**, 2–11.
Van Soest, P. J., Robertson, J. B. & Lewis, B. A. (1991). Symposium: carbohydrate methodology, metabolism and nutritional implications in dairy cattle methods for dietary fiber, neutral detergent fiber and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583–3597.
Walsh, K., O'Kiely, P., Moloney, A. P. & Boland, T. M. (2008*a*). 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. *Animal Feed Science and Technology* **144**, 257–278.
Walsh, K., O'Kiely, P., Moloney, A. P. & Boland, T. M. (2008*b*). 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. *Livestock Science* **116**, 223–236.
Wilkinson, J. M. & Phipps, R. H. (1979). The development of plant components and their effects on the composition of fresh and ensiled forage maize: 2. The effect of genotype, plant density and date of harvest on the composition of maize silage. *Journal of Agricultural Science, Cambridge* **92**, 485–491.
Woolford, M. K. (1975). Microbiological screening of food preservatives, cold sterilants and specific antimicrobial agents as potential silage additives. *Journal of the Science of Food and Agriculture* **26**, 229–237.
Woolford, M. K. (1984). *The Silage Fermentation*. New York, NY: Marcel Dekker, Inc.