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Effects of slurry application method and timing on grass silage quality

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SUMMARY

Small-scale silos (60-litre polyethylene barrels) were used to examine the chemical composition of grass silage after the application of slurry, at 40 m³/ha, at a range of timings, at two sites with contrasting rainfall; North Wyke, in Devon (high rainfall) and Reaseheath College, Cheshire (low rainfall). Grass plots (60 m²) received cattle slurry via surface broadcast (S), shallow injection (I) or surface placement by trailing shoe (T) techniques at 10, 6 or 2 weeks before an early silage (first) cut in May/June, and 6 or 2 weeks before a second cut in June/July. Control plots (C) received no slurry treatment. The harvested grass was compressed and sealed in the experimental silos and samples of the herbage at ensiling and of ensilage (after > 100-day fermentation) were analysed for various chemical components. Herbage yield was measured when the harvests were taken. Wetter than average weather conditions in both years resulted in silages with variable DM content (range 140–277 g/kg) being made at both sites. Generally, silages were poorly preserved with high pH and NH_4^+-N and low lactic acid contents. In particular, the silages from treatment S where slurry was applied 2 weeks prior to harvest exhibited characteristics indicative of clostridial growth, with high pH (range 4·0–5·2) and NH_4^+-N (106–213 g/kg total N) and low lactic acid (16–86 g/kg DM) contents. Damage to herbage caused by the injection tines on taller swards (treatments I at 6 and 2 weeks before cutting) was evident and the injection process was impeded by tall grass. This contributed to herbage contamination with soil and slurry on these treatments and, consequently, to poor silage fermentation. Silages made with slurry application method T at all timings showed improved fermentation characteristics compared with the other treatments, particularly at North Wyke. The results indicate that silage quality is unlikely to be compromised by slurry applications made in early spring, during February, March or even in April, where these are at agronomically sensible rates. Such practice will enable better utilization of slurry nitrogen (N), reducing risks of nutrient losses via leaching or surface runoff. Furthermore, shallow injection and, particularly, trailing shoe slurry application techniques may be used to increase flexibility of slurry management by allowing more immediate spreading before cutting than with conventional surface broadcasting, without detriment to silage quality.

INTRODUCTION

Livestock farming in the UK is becoming increasingly dependent on the social acceptance of farm management practices, particularly where issues of food hygiene, animal welfare and environmental pollution are concerned. Animal manures are produced in large quantities on UK farms (Smith & Chambers 1995) and, although recognized as an important source of plant nutrients and organic matter, are significant sources of pollution and frequently present problems of storage, spreading and cost-effective utilization (Pain 2000). On dairy farms, manure is often collected and stored as a semi-liquid slurry (faeces, urine, water, bedding material) which, when applied to grassland, presents a risk of herbage contamination and may affect the hygienic quality of grass for grazing and silage conservation. Common practice is for slurry to be surface broadcast, usually discharged from a tanker under pressure via a nozzle and splashplate (Smith *et al.* 2001). This practice may result in unacceptably high emission levels of ammonia (NH_3) and

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offensive odours, and may cause heavy contamination of herbage. To avoid rejection by grazing animals on predominantly grass farms, slurry is commonly spread across the grassland during late autumn and winter, and on silage conservation areas immediately after cutting. Recommendations for winter storage of manures are intended to minimize the risk of nutrient losses to surface water and of soil damage following applications during adverse conditions. The strategy also aims to avoid nitrate leaching at a time when nutrient uptake by the crop is low (Anon 1998; Smith *et al*., in press). Delaying applications until spring and summer effectively increases the amount of slurry to be spread at a time when clean herbage for grazing is at a premium and farmers perceive that the quality of silage crops may be affected (Tunney *et al*. 1980; O'Keily *et al*. 1993; Laws & Pain 1997). In recent years, alternative methods of slurry application for grassland such as shallow injection and trailing shoe application have been developed to reduce NH_3 emissions. These methods are effective in reducing the surface area, and hence the emitting surface, of slurry placed at low level in narrow bands either in slots cut in the soil (shallow, open-slot injection: *c*. 3–5 cm deep, 20 cm apart) or in even bands placed on the soil surface and below the grass canopy (trailing shoe: 3 cm wide, 20 cm apart) (Huijsmans *et al*. 1997). Reductions in NH_3 volatilization of $>80\%$ for shallow injection and 70% for trailing shoe compared with broadcast application have been measured (Frost 1994; Huijsmans *et al*. 1997; Lorenz & Steffens 1997; Smith *et al*. 2000). An important additional benefit of this new technology is the potential for reduced herbage contamination with slurry solids, which may allow spreading closer to silage cutting and, thereby, an extended window of opportunity for spreading without risk of adversely affecting silage fermentation quality. In circumstances where the normally accepted buffer between slurry spreading and grass cutting is compromised, e.g. as a result of a high workload in spring or adverse weather conditions, slurry application in narrow bands or placed below the grass canopy may be advantageous.

The current paper presents the results of an experiment undertaken at North Wyke in south-west England and at Reaseheath College of Agriculture in the English Midlands to examine the possible adverse effects of slurry application to grass prior to ensiling. The effects of slurry application method and timing on the chemical composition of grass for silage and ensilage are reported.

MATERIALS AND METHODS

Sites

A series of small grassland plots, each 3×20 m, were established at two sites with contrasting soil types and rainfall: the Institute of Grassland and Environmental Research (IGER), North Wyke Research Station, Devon (latitude 50·46° N, longitude 3·55° W) and Reaseheath College of Agriculture, Nantwich, Cheshire (latitude 53·05° N, longitude 2·31° W). The site at North Wyke was on poorly drained clay of the Hallsworth soil series, being characteristically waterlogged during the winter and early spring period (Findlay *et al*. 1984). The site at Reaseheath was on slowly permeable, silty loam/clay loam of the Crewe Association, overlying reddish clay drift (Furness 1978). Average annual rainfall is 1054 mm (1966–1995) at North Wyke and 710 mm (1961–1990) at Reaseheath. Swards were predominantly perennial ryegrass (*Lolium perenne* L.) at both sites.

Treatments and design

Data were collected for first and second cut silages made in 1998 and 1999. Three slurry application methods (surface broadcast, surface placement, shallow injection) were used at three different timings (10, 6 and 2 weeks) before a first silage cut and at two timings (6 and 2 weeks) before a second cut, providing a range of soil and crop conditions. In addition, there was an untreated (slurry) control plot (C) for each cut. All treatments were replicated within three randomized blocks, giving 51 plots in total at each site.

Fertilizer and slurry applications

Inorganic fertilizer nitrogen (N) (ammonium nitrate) was applied to the plots to provide additional N for plant growth and to neutralize the effects of N applied in slurry. Fertilizer was applied evenly across all the plots using a conventional tractor-mounted spreader incorporating a hopper and spinning-disc. Slurry was applied using a purpose-built, precision slurry applicator (Basford *et al*. 1996) which delivered measured amounts evenly across each plot and minimized the risk of variation in slurry application between treatments. Slurry was pumped from a tractor-mounted tanker to distribution elements mounted on a toolbar (1·6 m wide) drawn by a mini-tractor. Three different application methods were used:

1. Surface broadcast via splash-plates (S) – simulating conventional practice on most UK farms, slurry was pumped to outlet nozzles with splashplate attachments mounted 30 cm above ground and 30 cm apart.
2. Surface placement via trailing shoes (T) – slurry was placed in bands approximately 3 cm wide and 20 cm apart on the soil surface below the crop canopy.
3. Shallow slot injection (I) – slurry was placed in open V-shaped slots cut in the soil by two disc-coulters *c*. 5 cm deep, 3 cm wide and 20 cm apart.

These techniques have been described in detail elsewhere (Huijsmans *et al*. 1997). Two passes were made along the length of each plot, covering the plot width of 3 m. A slurry application rate of 40 m^3/ha was selected

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as standard for all treatments being a rate comparable to normal practice and one which, together with mineral fertilizer, would supply sufficient nutrients for treatment comparisons to be made. Target application timings were 10, 6 and 2 weeks before a first silage cut, and 6 and 2 weeks before a second cut. The treatments 10 weeks before first cut and 6 weeks before second cut were intended to simulate common practice with slurry applied to grassland in early spring and after the first silage harvest. The 2-week timing for both cuts aimed to coincide with a time when sward height ($> c.$ 10 cm) maximized the NH_3 abatement potential for slurry-application method T whilst also increasing the risk of herbage contamination for method S, so that a critical comparison could be made. At each site, slurry was used which had been collected from concrete yards and a milking parlour used by dairy cows and stored in an above-ground, circular tank. Slurry was taken from the stores at the time of the first application in each year, stored in sealed tanks and used throughout the year in an attempt to minimize the variability in slurry analysis between applications. On each spreading occasion, homogeneous slurry samples were taken from the slurry tanker for each application method and analysed for dry matter (DM; 18 h at 85 °C), total nitrogen (N; Kjeldahl technique), ammonium-N (NH_4^+-N; $Mg(OH)_2$ distillation; Anon 1986), phosphorus (P; HCl extraction and spectrophotometry; Anon 1986, Method 58, p. 181) and potassium (K; HCl extraction and flame photometry; Anon 1986, Method 62, p. 191). Samples were also analysed for pH (pH/mV meter model 3305 incorporating an electrode containing 3 M KCl; Jenway Ltd., Felsted, Essex CM6 3LB, UK) at North Wyke only.

Silage harvests and herbage yields

The times when the silage harvests were taken at both sites are shown in Fig. 1. All the treatment plots (for both first and second cuts) were cut when the first silage harvest was taken. Herbage from the plots allocated to the first cut was ensiled at this time, whilst herbage on plots for the second cut was discarded. The second cut plots were then prepared for fertilizer and slurry applications prior to the second silage harvest. Plots were re-allocated to treatments for the second year of the experiment. Herbage yield assessments were undertaken to coincide with each harvest. The herbage from a measured area of each plot (North Wyke: 2·8 m × 1·0 m; Reaseheath: first cut, 1·32 m × 18 m; second cut, 1·32 m × 20 m) was weighed immediately after cutting and before harvesting and a representative subsample ($c.$ 500 g) was taken for determination of DM content.

Ensiling procedure

Plots were mown to a height of $c.$ 5 cm at both sites using a tractor-mounted disc mower at North Wyke and a Hege plot harvester (Albertsen's EFTF, Løgstør, Denmark) at Reaseheath. Herbage was wilted in swaths for 18 h at North Wyke but was harvested soon after cutting at Reaseheath. At both sites, the herbage was picked up using a precision-chop forage harvester and was compressed by tramping in 60-litre polyethylene barrels (Harcostar Ltd., Huntingdon, Cambridgeshire) and, following sealing, fermentation was allowed to occur during indoor storage in cool conditions.

Chemical analysis

Representative herbage samples taken from the swath immediately before harvesting were analysed for DM (18 h at 85 °C), water-soluble carbohydrate (WSC; automated anthrone procedure; Thomas 1977) and total N at both sites, and buffering capacity (BC; aqueous extraction and electrometric titration; Playne & McDonald 1966) at North Wyke only. After a fermentation period of at least 100 days, representative sub-samples of silage were analysed for DM, digestible organic matter (DOM; a two stage technique; Jones & Hayward 1975), pH, NH_4^+-N, lactic (steam distillation with ceric sulphate; Elsden & Gibson 1954), acetic and butyric acids (ion exchange then gas liquid chromatography; Jones & Kay 1976), modified acid-detergent fibre (MADF; gravimetrically; Anon 1986, Method 30, p. 93) and ash (550 °C for 16 h). Metabolizable energy (ME, $15{\cdot}33 - 0{\cdot}152 \times \text{MADF}$) and crude protein (CP, $6{\cdot}25 \times NH_4^+$-N), were predicted.

Statistical analysis

Treatment means for all parameters were compared by analysis of variance using a randomized block design using Genstat 5 software (Genstat 5 Committee 1995). There were eight analyses for each variable, one for each cut at each site in each year. Data collected at each site were analysed separately.

RESULTS

Rainfall

At North Wyke in 1998, total rainfall during the March–July period was 140 % of the 30-year mean for this period (329 mm), with particularly large amounts occurring within 2 weeks of both the first and second silage cuts. In 1999, notably high rainfall occurred in April (171 % of average) and June (122 % of average). At Reaseheath, rainfall was also above average in 1998 with March, April and July being notably wet. In contrast, rainfall in 1999 between the first slurry application and the first silage cut was 32 % less than in the same period in 1998, and between the fourth slurry application and the second silage cut was 48 % less than in 1998.

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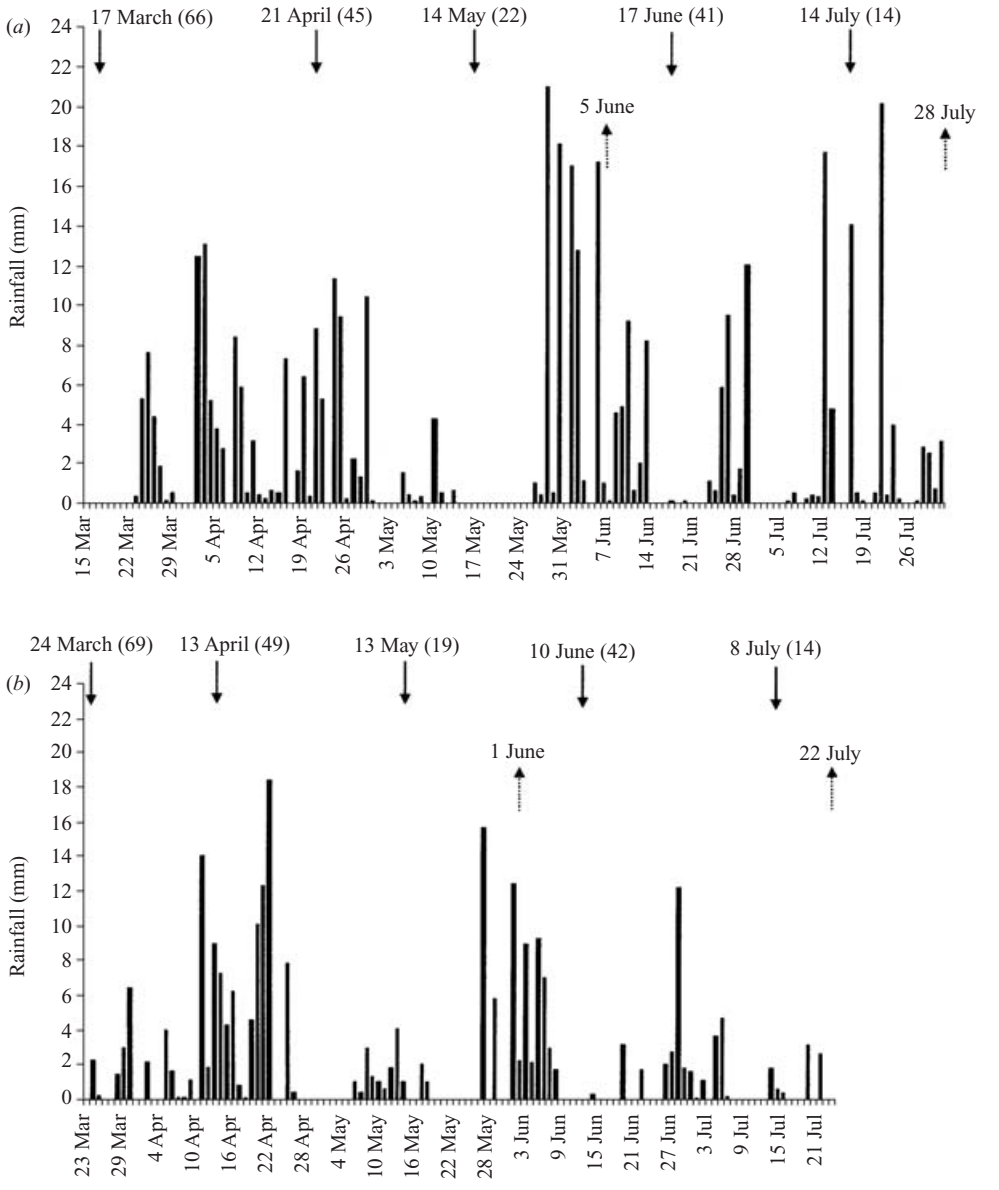


Fig. 1. For legend see facing page.

Slurry and N fertilizer applications

Times of slurry applications are shown in Fig. 1. The plot applicator performed well on cut and short swards and simulated closely the performance of field-scale equipment. Slurry injection 2 weeks before the first cut was impeded on tall swards at both sites, the disc coulters frequently failed to penetrate the ground sufficiently and crop damage and contamination with slurry occurred. In 1998 at Reaseheath, the method of application was, therefore, adapted to surface band spreading by disconnecting the hoses through which the slurry was pumped to the disc injectors and allowing them to trail over the standing crop. It was possible to apply the slurries earlier in spring (*c.* 2 weeks) at Reaseheath than at North Wyke. Nutrient contents of the slurries used at each site were variable (Table 1). Slurries used at North Wyke were dilute compared with those used at Reaseheath. Consequently, N contents of slurries and organic N supply to the treatment plots at North Wyke were comparatively low (Table 2).

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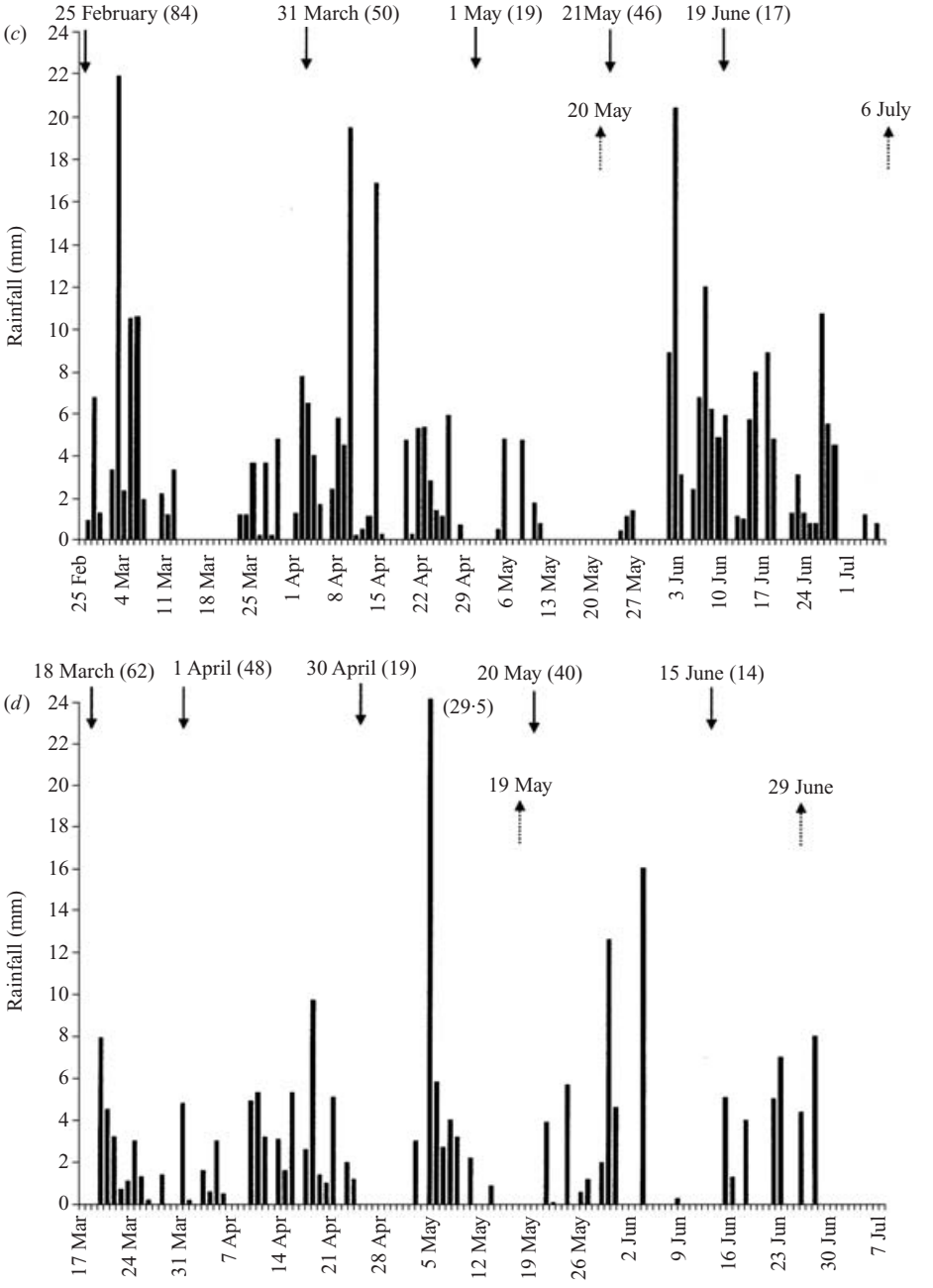


Fig. 1. Daily rainfall patterns during the period from the first slurry application until the second silage cut for (*a*) North Wyke 1998, (*b*) North Wyke 1999, (*c*) Reaseheath 1998 and (*d*) Reaseheath 1999. Times of slurry applications (↓) and silage cuts (↑) are indicated. Time (days) between each slurry application and the subsequent grass cut is shown in parentheses.

Times and rates of inorganic N fertilizer applications are shown in Table 2. The amounts of fertilizer required for the first silage cuts were applied in two dressings approximately 2 weeks apart at North Wyke in 1998 and 1999 and 4 weeks apart at Reaseheath in 1998. A single application was used before the first cut at Reaseheath in 1999 and for the second cuts in both years at both sites. Mean total N inputs from organic and inorganic sources (Table 2) were higher in each year at Reaseheath (overall range: 145 to 182 kg/ha at

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Table 1. *Details of slurry composition. Data are means of all application methods and timings for each silage cut in each year*

Site	Year	Cut	DM (g/kg)	Total N (g/l)	NH_4^+-N (g/l)	Total P (g/l)	Total K (g/l)	pH
North Wyke	1998	1	40	2·0	1·3	0·4	2·6	7·1
	1998	2	42	2·0	1·2	0·4	2·0	7·2
	1999	1	43	1·5	1·2	0·4	2·7	7·1
	1999	2	44	1·4	1·1	0·4	2·4	7·1
Reaseheath	1998	1	68	3·7	2·0	0·7	2·9	ND
	1998	2	52	2·6	1·4	0·5	1·8	ND
	1999	1	59	4·1	2·4	0·6	3·0	ND
	1999	2	62	4·8	2·6	1·0	3·4	ND

ND, not determined.

Table 2. *Times and rates (kg/ha) of inorganic N inputs, rates (kg/ha) of total N and NH_4^+-N supplied as organic N, and total N application rates (kg/ha) from both inorganic and organic sources at North Wyke and Reaseheath in both years*

			Inorganic N				Organic N		
Site	Year	Cut	First application		Second application		Total N	NH_4^+-N	Total N applied
North Wyke	1998	1	3 Mar	60	16 Mar	42	80	52	182
	1998	2	7 Jun	88			78	48	166
	1999	1	5 Mar	58	21 Mar	40	61	48	159
	1999	2	2 Jun	90			55	44	145
Reaseheath	1998	1	19 Feb	48	20 Mar	36	147	78	231
	1998	2	21 May	72			104	54	176
	1999	1	24 Mar	90			166	92	256
	1999	2	21 May	90			191	104	281

North Wyke; 176 to 281 kg/ha at Reaseheath) with the difference between sites being mainly because of the variation in the organic N supply.

Silage harvests and herbage yields

First cuts for silage were delayed at both sites in both years because of wet weather and ground conditions. Periods between spreading and cutting ranged from 14 to 69 days at North Wyke and from 14 to 84 days at Reaseheath (Fig. 1). In both years, silage cuts were earlier at Reaseheath than at North Wyke by approximately 2 weeks for the first cut and 3 weeks for the second cut. Mean herbage DM yield (Tables 3–6) was generally higher for treatment T than treatments I or S with the difference being significant at Reaseheath for the second cut in 1998 ($P<0·05$) and the first cut in 1999 ($P<0·001$). Herbage yields decreased with decreasing time between slurry applications and grass harvests for all application methods at both sites. Mean DM yield was considerably lower in the second harvest than in the first in both years.

Chemical composition of herbage and ensilage

Chemical composition of herbage at ensiling showed considerable variation between sites and years (Tables 3–6). Trends in increasing herbage DM content with decreasing time between slurry applications and silage harvests were apparent in both years, and there were significant increases in herbage DM content for slurry applications only 2 weeks before harvest compared with earlier applications, and for application method S compared with methods I and T. Herbage total N content showed similar trends with slurry application timing with significantly higher N content when applications were 2 weeks before harvesting compared with earlier applications ($P<0·05$, Reaseheath, second cut, 1999; $P<0·01$, North Wyke, first cut, 1998 and 1999, Reaseheath, first cut, 1998; $P<0·001$, North Wyke, second cut, 1999). Water-soluble carbohydrates (analysed at North Wyke only) were present in sufficient quantities in all the ensiled grass crops so as not to limit microbial growth in silage, with the exception of treatment S when slurry was applied 2 weeks before the second harvest in 1999. Herbage buffering

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Table 3. *Herbage dry matter yield and the chemical composition of herbage at ensiling and silage for both silage cuts at North Wyke in 1998*

		Injection*			Trailing shoe*			Surface*				*P*		
	Control	10W	6W†	2W	10W	6W†	2W	10W	6W†	2W	S.E.	Method	Timing	Interaction
First cut (18 D.F.)														
Herbage‡														
DM yield (t/ha)	8·5	8·3	7·8	6·8	8·2	7·7	6·4	7·9	8·3	6·4	1·15	0·974	0·215	0·992
DM (g/kg)	179	168	182	202	163	176	192	174	173	216	7·9	0·251	<0·001	0·524
Total N (g/kg DM)	19	23	22	25	21	20	24	22	21	24	1·0	0·095	0·003	0·964
WSC (g/kg DM)	97	69	94	86	80	95	78	79	89	80	8·5	0·978	0·078	0·796
BC (mE/kg DM)	291	288	294	238	279	293	259	286	280	298	13·3	0·408	0·088	0·095
Silage§														
DM (g/kg)	151	155	149	155	145	142	157	156	165	166	10·1	0·242	0·594	0·894
DOM (% DM)	555	553	581	554	563	565	559	548	564	557	5·8	4·01	0·090	1·75
ME (MJ/kg DM)	10·4	10·5	10·8	10·5	10·4	10·6	10·6	10·4	10·4	10·2	0·11	0·022	0·194	0·436
CP (g/kg DM)	133	153	167	182	141	145	175	141	151	185	5·6	0·025	<0·001	0·459
pH	3·9	4·2	3·9	4·1	3·8	3·9	3·9	3·8	3·9	4·7	0·14	0·057	0·009	0·011
NH_4^+-N (g/kg total N)	80	88	86	113	85	89	79	84	96	145	7·4	0·003	<0·001	0·002
Lactic acid (g/kg DM)	84	91	84	64	92	82	82	93	85	37	6·2	0·049	<0·001	0·007
Acetic acid (g/kg DM)	20	22	22	25	21	24	112	23	19	19	29·8	0·363	0·374	0·433
Butyric acid (g/kg DM)	0	0	0	0	0	0	0	0	0	0				
Ash (g/kg DM)	76	83	91	92	82	87	89	83	86	102	2·9	0·194	<0·001	0·064
Second cut (12 D.F.)														
Herbage‡														
DM yield (t/ha)	4·0		2·4	2·0		3·3	2·5		3·4	1·9	0·32	0·124	0·006	0·270
DM (g/kg)	142		128	143		125	135		123	144	15·0	0·269	0·785	0·271
Total N (g/kg DM)	23		23	32		26	51		26	29	8·3	0·332	0·087	0·449
WSC (g/kg DM)	146		142	91		119	271		125	81	58·6	0·276	0·693	0·185
BC (mE/kg DM)	267		220	271		248	277		234	248	20·5	0·562	0·085	0·675
Silage§														
DM (g/kg)	164		152	145		148	143		141	140	11·6	0·790	0·674	0·967
DOM (% DM)	608		615	579		628	560		613	493	48·0	6·07	0·810	6·84
ME (MJ/kg DM)	10·9		11·0	11·1		11·1	11·2		11·0	10·3	0·11	0·001	0·082	0·008
CP (g/kg DM)	167		168	221		178	209		172	206	7·0	0·751	<0·001	0·275
pH	3·8		3·8	4·1		3·8	3·9		3·8	5·2	0·07	<0·001	<0·001	<0·001
NH_4^+-N (g/kg total N)	55		58	76		53	67		68	174	12·0	<0·001	<0·001	0·004
Lactic acid (g/kg DM)	97		104	90		114	95		93	16	8·7	<0·001	<0·001	0·006
Acetic acid (g/kg DM)	30		24	39		26	29		24	29	5·6	0·617	0·120	0·583
Butyric acid (g/kg DM)	0		0	0		0	0		0	0				
Ash (g/kg DM)	79		78	78		78	80		80	82	3·5	0·413	0·109	0·563

* Slurry application timings: 10W, 10 weeks; 6W, 6 weeks; 2W, 2 weeks before cutting.
† Slurry application timing 6W second cut was applied to a cut sward. All other applications were made to swards with varying amounts of grass cover.
‡ DM, dry matter; WSC, water-soluble carbohydrate; BC, buffering capacity.
§ DOM, digestible organic matter; ME, metabolizable energy; CP, crude protein; NH_4^+-N, ammonium N.

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Table 4. *Herbage dry matter yield and the chemical composition of herbage at ensiling and silage for both silage cuts at North Wyke in 1999*

		Injection*			Trailing shoe*			Surface*				Significance		
	Control	10W	6W†	2W	10W	6W†	2W	10W	6W†	2W	S.E.	Method	Timing	Interaction
First cut (18 D.F.)														
Herbage‡														
DM yield (t/ha)	6·3	7·0	6·7	4·3	7·5	5·9	6·4	6·7	5·9	6·3	1·00	0·795	0·238	0·570
DM (g/kg)	164	167	172	199	172	170	189	179	154	196	9·6	0·922	0·004	0·518
Total N (g/kg DM)	10	11	12	15	11	12	15	9	12	11	0·9	0·011	0·002	0·357
WSC (g/kg DM)	109	102	105	109	105	106	95	117	89	92	6·3	0·529	0·168	0·065
BC (mE/kg DM)	290	320	329	276	273	311	291	287	295	266	14·7	0·127	0·034	0·346
Silage§														
DM (g/kg)	157	157	164	187	148	154	165	154	160	178	7·6	0·120	0·003	0·918
DOM (% DM)	555	564	591	594	567	563	574	574	552	544	6·9	<0·010	9·37	0·040
ME (MJ/kg DM)	10·4	10·6	10·7	10·9	10·4	11·1	10·7	10·6	10·5	10·1	0·22	0·124	0·446	0·165
CP (g/kg DM)	141	151	156	174	141	148	162	135	143	167	9·0	0·260	0·007	0·977
pH	4·0	3·9	3·9	3·9	3·9	3·9	3·9	4·0	4·0	4·8	0·13	0·006	0·009	0·012
NH_4^+-N (g/kg total N)	77	82	85	69	87	79	78	61	95	162	12·7	0·032	0·061	0·002
Lactic acid (g/kg DM)	93	100	100	86	110	95	92	85	87	27	11·9	0·006	0·012	0·163
Acetic acid (g/kg DM)	22	23	24	19	22	20	23	14	19	24	4·3	0·660	0·849	0·550
Butyric acid (g/kg DM)	0	0	0	0	0	0	0	0·2	0	1·5				
Ash (g/kg DM)	105	108	112	117	110	112	112	115	113	132	3·2	0·007	0·004	0·063
Second cut (12 D.F.)														
Herbage‡														
DM yield (t/ha)	3·6		4·0	3·6		4·9	3·6		4·5	4·5	0·39	0·250	0·119	0·284
DM (g/kg)	249		211	252		225	238		228	326	12·3	0·004	<0·001	0·015
Total N (g/kg DM)	21		22	29		24	28		21	29	1·4	0·620	<0·001	0·268
WSC (g/kg DM)	158		118	116		113	110		131	76	10·2	0·455	0·037	0·039
BC (mE/kg DM)	256		267	273		257	268		267	256	16·0	0·840	0·868	0·766
Silage§														
DM (g/kg)	221		197	232		194	224		193	277	9·0	0·033	<0·001	0·019
DOM (% DM)	617		608	612		600	603		592	552	9·1	0·030	1·77	0·490
ME (MJ/kg DM)	10·5		10·6	11·0		10·5	10·9		10·5	10·6	0·09	0·047	<0·001	0·198
CP (g/kg DM)	149		159	189		157	191		152	182	4·7	0·255	<0·001	0·912
pH	4·3		4·3	4·3		4·4	4·1		4·3	5·1	0·12	0·004	0·107	0·004
NH_4^+-N (g/kg total N)	82		84	73		83	69		81	106	7·2	0·066	0·947	0·036
Lactic acid (g/kg DM)	80		83	62		64	82		66	21	6·8	0·001	0·014	0·002
Acetic acid (g/kg DM)	10		16	14		7	17		7	8	3·1	0·083	0·269	0·240
Butyric acid (g/kg DM)	0		0	0		0	0		0	1·9				
Ash (g/kg DM)	117		124	124		121	121		126	143	3·8	0·010	0·080	0·058

* Slurry application timings: 10W, 10 weeks; 6W, 6 weeks; 2W, 2 weeks before cutting.
† Slurry application timing 6W second cut was applied to a cut sward. All other applications were made to swards with varying amounts of grass cover.
‡ DM, dry matter; WSC, water-soluble carbohydrate; BC, buffering capacity.
§ DOM, digestible organic matter; ME, metabolizable energy; CP, crude protein; NH_4^+-N, ammonium N.

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Table 5. *Herbage dry matter yield and the chemical composition of herbage at ensiling and silage for both silage cuts at Reaseheath in 1998*

		Injection*			Trailing shoe*			Surface*				Significance		
	Control	10W	6W†	2W‡	10W	6W†	2W	10W	6W†	2W	S.E.	Method	Timing	Interaction
First cut (18 D.F.)														
Herbage§														
DM yield (t/ha)	6·5	6·4	5·9	6·0	6·3	6·4	5·9	6·6	6·8	6·3	0·17	0·194	0·312	0·080
DM (g/kg)	173	176	156	169	166	166	177	177	170	173	3·3	0·438	0·104	0·405
Total N (g/kg DM)	23	22	26	24	21	27	28	20	23	27	1·0	0·473	0·006	0·501
Silage$														
DM (g/kg)	190	190	193	197	184	185	201	189	194	208	3·3	0·396	0·016	0·782
DOM (% DM)	693	717	723	703	700	700	703	703	700	690	5·9	1·39	5·26	8·04
ME (MJ/kg DM)	11·1	11·4	11·6	11·3	11·2	11·2	11·2	11·3	11·2	11·1	0·09	0·201	0·577	0·851
CP (g/kg DM)	195	191	223	205	191	206	206	194	202	203	3·5	0·357	0·005	0·333
pH	4·3	4·0	4·2	4·0	4·3	4·3	4·0	4·2	4·1	4·0	0·07	0·365	0·249	0·726
NH_4^+-N (g/kg total N)	153	117	110	110	130	147	123	137	113	123	1·2	0·475	0·873	0·891
Lactic acid (g/kg DM)	75	86	80	91	84	81	90	77	91	86	4·5	0·470	0·748	0·896
Acetic acid (g/kg DM)	9	7	5	11	7	12	9	5	8	11	2·1	0·805	0·380	0·760
Butyric acid (g/kg DM)	24	13	8	8	27	20	10	16	10	9	4·0	0·257	0·265	0·905
Ash (g/kg DM)	93	85	91	90	97	96	91	92	91	94	1·9	0·116	0·895	0·502
Second cut (12 D.F.)														
Herbage§														
DM yield (t/ha)	2·6		2·9	1·4		3·6	2·4		2·5	2·3	0·14	0·014	<0·001	0·055
DM (g/kg)	150		129	152		130	136		135	161	2·1	0·005	<0·001	0·037
Total N (g/kg DM)	23		26	29		23	27		24	27	0·97	0·259	0·038	0·850
Silage$														
DM (g/kg)	169		178	179		179	176		180	194	2·0	0·029	0·201	0·082
DOM (% DM)	700		693	707		683	700		697	690	5·2	6·28	3·09	4·00
ME (MJ/kg DM)	11·2		11·1	11·3		10·9	11·2		11·2	11·1	0·08	0·546	0·244	0·347
CP (g/kg DM)	201		199	206		207	208		199	201	3·4	0·517	0·522	0·861
pH	4·1		4·0	3·9		3·9	3·9		3·9	4·3	0·04	0·121	0·177	0·026
NH_4^+-N (g/kg total N)	120		107	103		103	100		100	137	4·2	0·096	0·122	0·028
Lactic acid (g/kg DM)	96		90	109		97	117		104	74	2·8	0·072	0·048	0·202
Acetic acid (g/kg DM)	6		4	11		6	8		6	13	1·3	0·551	0·013	0·440
Butyric acid (g/kg DM)	10		3	6		1	3		4	13	1·7	0·090	0·062	0·526
Ash (g/kg DM)	93		89	93		92	95		90	95	1·2	0·430	0·023	0·843

* Slurry application timings: 10W, 10 weeks; 6W, 6 weeks; 2W, 2 weeks before cutting.
† Slurry application timing 6W second cut was applied to a cut sward. All other applications were made to swards with varying amounts of grass cover.
‡ Shallow injection replaced by trailing hose slurry application for the first silage cut only.
§ DM, dry matter.
$ DOM, digestible organic matter; ME, metabolizable energy; CP, crude protein; NH_4^+-N, ammonium N.

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Table 6. *Herbage dry matter yield and the chemical composition of herbage at ensiling and silage for both silage cuts at Reaseheath in 1999*

		Injection*			Trailing shoe*			Surface*				Significance		
	Control	10W	6W†	2W	10W	6W†	2W	10W	6W†	2W	S.E.	Method	Timing	Interaction
First cut (18 D.F.)														
Herbage‡														
DM yield (t/ha)	4·1	8·8	5·8	5·0	9·4	8·7	7·2	6·4	5·9	5·4	0·40	<0·001	0·003	0·251
DM (g/kg)	187	165	167	190	166	169	185	169	163	200	4·6	0·810	<0·001	0·769
Total N (g/kg DM)	22	24	26	24	24	24	25	23	24	28	1·1	0·933	0·477	0·536
Silage§														
DM (g/kg)	194	190	186	204	186	182	204	187	182	207	2·9	0·813	<0·001	0·962
DOM (% DM)	690	663	660	673	670	670	670	677	657	667	4·9	8·04	4·510	6·66
ME (MJ/kg DM)	11·0	10·6	10·6	10·8	10·7	10·7	10·7	10·8	10·6	10·7	0·08	0·878	0·546	0·664
CP (g/kg DM)	153	162	162	160	143	149	163	157	147	167	4·4	0·328	0·222	0·524
pH	4·6	4·7	4·9	4·5	4·5	4·4	4·4	4·7	4·8	4·5	0·05	0·005	0·007	0·249
NH_4^+-N (g/kg total N)	227	257	310	220	233	247	200	257	320	213	11·8	0·068	<0·001	0·620
Lactic acid (g/kg DM)	54	48	37	65	62	61	65	50	44	64	2·6	0·031	<0·001	0·502
Acetic acid (g/kg DM)	18	28	31	27	28	30	28	25	28	31	1·6	0·960	0·501	0·722
Butyric acid (g/kg DM)	10	8	19	6	5	9	1	13	20	1	1·8	0·057	<0·001	0·380
NDF (g/kg DM)	540	567	571	538	551	545	543	544	574	537	6·9	0·487	0·066	0·423
Ash (g/kg DM)	96	99	102	98	97	98	97	100	99	100	1·3	0·373	0·839	0·843
Second cut (12 D.F.)														
Herbage‡														
DM yield (t/ha)	4·0		3·5	2·4		3·5	2·6		3·3	2·8	0·23	0·961	0·026	0·704
DM (g/kg)	185		158	169		145	170		161	217	3·5	<0·001	<0·001	0·010
Total N (g/kg DM)	25		29	29		31	31		25	28	0·9	0·062	0·626	0·627
Silage§														
DM (g/kg)	192		192	204		193	212		189	240	2·7	0·014	<0·001	0·003
DOM (% DM)	700		683	703		690	687		703	653	6·4	3·91	2·28	0·200
ME (MJ/kg DM)	11·2		10·9	11·3		10·0	11·0		11·2	10·5	0·10	0·342	0·411	0·020
CP (g/kg DM)	160		179	183		168	188		164	182	2·8	0·311	0·004	0·243
pH	4·5		4·3	4·3		4·3	4·5		4·2	4·2	0·02	0·002	0·230	0·082
NH_4^+-N (g/kg total N)	197		156	150		180	153		153	150	10·8	0·687	0·439	0·800
Lactic acid (g/kg DM)	55		65	82		67	49		74	71	1·7	0·213	0·759	0·452
Acetic acid (g/kg DM)	18·7		18·0	23·0		22·7	17·3		24·7	22·7	1·6	0·395	0·740	0·213
Butyric acid (g/kg DM)	6·5		0·7	0·5		0·5	1·2		0·5	0·5	1·2	0·985	0·921	0·976
NDF (g/kg DM)	529		527	493		540	521		513	530	8·1	0·375	0·326	0·221
Ash (g/kg DM)	99		100	103		97	102		94	101	0·8	0·039	<0·001	0·205

* Slurry application timings: 10W, 10 weeks; 6W, 6 weeks; 2W, 2 weeks before cutting.
† Slurry application timing 6W second cut was applied to a cut sward. All other applications were made to swards with varying amounts of grass cover.
‡ DM, dry matter.
§ DOM, digestible organic matter; ME, metabolizable energy; CP, crude protein; NH_4^+-N, ammonium N.

capacity (BC) (analysed at North Wyke only) was generally <300 mE/kg DM and treatment differences were non-significant, with the exception of the first harvest in 1999 when the BC of herbage with slurry applied 2 weeks before the harvest was significantly ($P<0{\cdot}05$) lower than for the earlier slurry applications. Considerable variability was shown in silage fermentation characteristics between and within both years and at both sites (Tables 3–6). Generally, silages (slurry-treated and slurry-untreated) were wet (<200 g/kg DM) and poorly preserved. In particular, the silages made at Reaseheath exhibited poor fermentation characteristics with low DM contents (<200 g/kg) and high pH (>4) and NH_4^+-N contents (>100 g/kg total N), particularly for the first cut in 1999. At both sites, NH_4^+-N contents and pH increased and lactic acid contents decreased with reducing time between slurry applications and the silage harvests. Silages with the poorest fermentation characteristics were invariably made on treatment S when slurry was applied 2 weeks before harvesting at both sites. Significant amounts of butyric acid were measured in first cut silages in both years at Reaseheath. Low DOM (<650 g/kg DM) and ME ($<10{\cdot}8$ MJ/kg DM) contents (North Wyke, all cuts) indicated that the herbage was probably cut at a later than optimum stage of growth. Crude protein contents were generally greater for Reaseheath than for North Wyke and also when slurry was applied 2 weeks before cutting, compared with 6 or 10 weeks.

DISCUSSION

Well-preserved silage is characterized by a high concentration of lactic acid (typically 80–120 g/kg DM for grass silage), low butyric acid content (<5 g/kg DM), low pH (3·8–4·2) and an NH_3-N concentration below 100 g/kg total N (McDonald 1981). Adequate levels of readily available substrate as WSC (>25 g/kg fresh) are required in the grass to encourage the growth of lactic acid bacteria and the production of lactic acid. Buffering capacity, i.e. the plant's ability to neutralize pH change, must be sufficiently low (normally *c*. 380 mE/kg DM in perennial ryegrass) so as not to counteract the production of lactic and acetic acids and the accompanying reduction in pH. Although it is possible to make well-preserved silage from wet herbage (>80% moisture) a plentiful supply of soluble carbohydrates is required if a pH of about 4·0 is to be achieved. It is normally accepted that this level of acidity is required to inhibit clostridial activity although lower pH may be required in very wet silage (McDonald *et al.* 1962; McDonald 1981). The most important contamination risk when slurry is applied to grass crops prior to ensiling is the addition of clostridia. These bacteria are ingested by animals in soil-contaminated forage and fodder crops and, when added to crops for silage, ferment sugars and lactic acid to produce butyric acid and other undesirable fermentation byproducts such as carbon dioxide and hydrogen. This undesirable fermentation process is indicated by a rise in pH and NH_3-N content and a reduction in lactic acid content (Kemble 1956; McDonald 1981).

Silages were made at both sites in both years during periods of wet weather and exhibited lower than optimum moisture contents. Fermentation aids such as chemical and biological additives were not used. A short period of wilting at North Wyke may have accounted for the only marginal improvement in fermentation qualities in silage made at this site. Silages with high moisture content provide the ideal conditions for adverse effects of contamination with soil and slurry to be examined. At both sites, silage fermentation was poor for treatment S, where slurry was applied 2 weeks prior to harvest, characterized by unacceptably high NH_4^+-N content and pH and low lactic acid content for both silage cuts. Moreover, on visual examination, this silage appeared to be darker in colour indicating overheating during the ensiling process and this, together with a musty odour, was indicative of contamination with slurry organic matter residues. The silages made on treatment I where slurry had been applied 2 weeks before harvest, particularly at North Wyke in 1999, also exhibited the characteristics of poor fermentation. It was possible that herbage contamination with soil was an important factor in the fermentation process and, indeed, may have contributed to the poor fermentation of the silages made on treatment I when slurry was applied 6 and 2 weeks prior to harvest. Crop damage by wheeling and flattening caused by the application machinery was common for all slurry application methods. For method I, additional damage occurred on taller crops by the severing action of the disc coulters and herbage contamination with soil and slurry was more evident on this treatment. In contrast, silages made 2 weeks after slurry application via trailing shoes were generally well fermented and comparable with the untreated controls (C). The advantage of using the trailing shoe technique on tall swards was evident at both sites. Although wheeling damage still occurred, the shoe attachments through which the slurry was delivered to the soil surface moved freely through the sward and slurry placement was unimpeded. Advantages in narrow-band slurry application techniques have also been demonstrated on grazed swards by Laws & Pain (2002) who reported reduced aversion over a shorter time to swards with slurry applied by trailing shoe or shallow disc injection compared with conventional surface broadcasting.

Although herbage DM yield was generally low, the trend for increasing herbage DM content with reducing time between spreading and cutting was consistent for all slurry application methods. This may have been caused by leaf desiccation at a time of

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substantial leaf area index and a reduced period for compensatory growth before cutting. The higher rates of slurry-N application at Reaseheath may have accounted for the generally poorer quality of the silages made at this site. In particular, high levels of non-protein N in the grass at ensiling may have been the cause of high ammonia-N levels in silage which were measured in all cases at Reaseheath. It was apparent that the late broadcast applications of slurry prior to cutting exacerbated NH_4^+-N levels in silage. One notable impact of late slurry addition was the significant increase in crude protein levels in silage.

Anaerobic conditions are essential for the production of lactic acid bacteria. The experimental silos used in these experiments were perfectly sealed and created ideal conditions for the fermentation process. In practice, silage clamps may not be completely airtight and localized centres of aerobic deterioration promoting multiplication of harmful microorganisms such as enterobacteria and clostridia may occur. The addition of slurry to herbage prior to harvesting increases these populations on the growing herbage (Davies *et al*. 1996) and in silage (Rammer *et al*. 1994). The grass at ensiling had lower than optimum DM contents at both sites and no additives were used to counteract any possible negative effects on silage fermentation caused by slurry addition. Commonly, chemical additives such as formic acid and bacterial inoculants are used during the silage-making process to induce rapid pH decline and to encourage lactic acid production. Animal slurries contain potentially harmful bacteria (Mawdsley *et al*. 1995) which may have major implications for the timing of slurry applications in relation to harvesting (Östling & Lingren 1991; Davies *et al*. 1996) and other agronomic practices. Herbage contamination following slurry application by narrow band placement techniques is much reduced compared with conventional surface broadcasting. However, the viability of pathogens in slurry and the risk of dispersal to surface and sub-surface water supplies, and to the wider environment, needs further investigation for all slurry application methods.

It is difficult to say to what extent slurry addition alone may have affected silage quality. Clearly, the combined effects of slurry addition and the physical damage to the sward caused by the slurry applicator and other field operations was, at times, detrimental to both herbage yield and silage quality. The reduction in herbage yield with decreasing time between slurry applications and grass harvests which was evident at both sites in both years was most probably a result of wheelings made by the slurry applicator and mini-tractor, and damage to the grass crop caused by the slurry applicator tines. Disc injection on tall swards flattened and severed the herbage along the lines of the injection slots and the injection process was impeded. In contrast, the passage of trailing shoes caused little damage to tall swards and the slurry was deposited below the grass canopy with minimal contamination of herbage. Wheeling damage was greater and crop recovery time was longer on tall rather than short swards. These observations are confirmed by the significant improvement in herbage yield for treatment T on two occasions (second cut in 1998 and first cut in 1999) at Reaseheath and in silage fermentation quality generally, for treatments T and I compared with S. Surface broadcast application of slurry caused gross contamination of the herbage, particularly when slurry was applied after a period of re-growth. Herbage contamination was evident for longer if drying occurred and slurry adhered to the leaf lamina in the period immediately after spreading, even when such conditions were followed by periods of heavy rainfall.

Where slurry applications were by trailing shoe or shallow injection, it was evident that good fermentation was more dependent on the quality of grass at ensiling and the prevailing weather conditions. Possible adverse effects of slurry on silage fermentation properties, whether application was by novel (methods T or I) or conventional (method S) methods were reduced when slurry was applied to swards immediately after cutting (i.e. six weeks before the second cut) rather than applications to taller swards at other times of year. It was evident, therefore, that these alternative methods of slurry application, initially developed for their NH_3 abatement potential (Huijsmans *et al*. 1997), offer important additional benefits in reduced herbage contamination with implications for improved herbage utilization under cutting and grazing.

Crop damage and possible yield depression as a result of slurry smothering and scorch effects were shown by Smith *et al*. (1995) to be strongly related to both application timing and rate of slurry solids. However, damage from conventional slurry application timings is likely to be minimal, providing application rate is limited to agronomically sensible levels (i.e. based on slurry nutrient content and crop demand) (Anon 2000). In the case of injection, of course, the cutting and flattening effects of the injection elements also need to be considered. Overall, therefore, the degree of contamination and physical damage is influenced significantly by the timing of these operations, the rate of slurry applied, soil type, soil conditions, the state of the crop (e.g. height) and the weather. Contamination and crop damage is ameliorated to some extent by rainfall and by crop recovery over time. It is important, therefore, that attention is paid to avoid field operations when the soil is wet and when the crop is tall, and to encourage practices which protect the crop against damage and contamination by soil and slurry. Management practices, such as rolling grassland in early spring and avoiding travelling on the crop unnecessarily at any time, can make an important contribution to an overall strategy to allow the successful integration of animal slurries into grass silage production systems.

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CONCLUSIONS

Every opportunity should be taken to apply slurry when soil and weather conditions and crop growth are optimal. This approach would also be consistent with best utilization of slurry nutrients. Shallow disc injection and, in particular, trailing shoe application of cattle slurry to grassland were successful in reducing herbage contamination and improving silage quality compared with conventional surface broadcasting. Shallow injection should be used on short swards wherever possible, preferably after cutting, to prevent physical damage to the crop. Slurry can be applied by trailing shoes on taller swards without fear of negative effects on silage fermentation, thus allowing an extended opportunity for spreading operations and, hence, much greater flexibility in slurry application timing.

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