THE USE OF SEWAGE SLUDGES AS NITROGENOUS FERTILIZERS FOR GRASSLAND

Nicholas John Hutchings

Ph.D.

1982

ACKNOWLEDGEMENTS

I would like to thank the Severn Trent Water Authority for their financial assistance, for the provision of the sludges and the loan of equipment. The help and advice received from the staff of the Strongford, Malvern and Nottingham laboratories and Market Drayton STW is also gratefully acknowledged. I am indebted to John Fenlon for his advice concerning statistics and for some of the statistical analyses.

I would like to thank Dr A Polwart for supervising this project and Prof. J B Lloyd for the use of the facilities of the Department of Biological Sciences.

The technical assistance of Ian Burns, Steve Jones, Nigel Bowers, and Donna Harvey in the laborious and often unpleasant field work associated with this project is gratefully acknowledged.

I would particularly like to thank Dr B Chapman for his patience and diplomacy whilst liaising between myself and the Severn Trent Water Authority.

I would not have been able to complete this project without the support (moral and financial), typing skill and understanding of Margit Schacht.

ABSTRACT

The value of liquid anaerobically digested (LDS), liquid activated (LAS) and pressed cake (PC) as nitrogen fertilizers for grassland was compared to that of ammonium nitrate (AN) in a field trial containing 16 treatments applied to 1.5m x 10m plots replicated four times at each of two sites over two years. The grass was harvested four times per year.

The availability of the nitrogen in LDS, LAS and PC based on the nitrogen yield response was 46%, 50% and 16% respectively on a sandy soil and 35%, 48% and 20% respectively on a clay soil. Gaseous losses may have reduced the availability of the nitrogen in the liquid sludges on the clay soil. The water in the sludges had little effect on the availability of the nitrogen.

The effect of the sludges on the dry matter yield and digestibility and the concentrations of crude protein, water soluble carbohydrate, nitrate-nitrogen, calcium and magnesium in the grass was similar to that of AN supplying the same available nitrogen. The LDS slightly raised the concentration of potentially toxic elements in the grass, probably due to the foliar retention of sludge solids. A laboratory experiment found the foliar retention to vary with the sludge type and solids content.

The sludges increased the concentrations of organic matter, potentially toxic elements, and extractable phosphate, and the earthworm density in the soil. The AN acidified the soil more than the sludges.

The response of a grass/clover sward in 30 cm diameter pots in the field to the sludges and AN was lower than that of the pure grass sward. The response to the sludges depended upon the availability and rate of release of the sludge nitrogen.

The speed of release of sludge nitrogen justifies considering liquid sludges as fast-acting fertilizers although the variation in the nitrogen availability reduces their value for grassland management.

ABBREVIATIONS

ADAS	Agricultural Developement and Advisory Service
AN	Ammonium nitrate
CEC	Cation exchange capacity
CP	Crude protein
CV	Coefficient of variation
cv	Cultivar
DM	Dry matter
DOE	Department of the Environment
EEC	European Economic Community
LAS	Liquid activated sludge
LDS	Liquid digested sludge
LIN	Linear
LPS	Liquid primary sludge
MADF	Modified acid detergent fibre
MAFF	Ministry of Agriculture
N source	A material which supplies nitrogen
NWC	National Water Council
p	Page
PC	Pressed cake sludge
PTE	Potentially toxic elements
QUAD	Quadratic
RESID	Residual
STW	Sewage treatment works
WSC	Water soluble carbohydrates

Also see Glossary, p 164

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Introduction

Sewage sludges (sludges) are a by-product of the purification of wastewater prior to its discharge to a watercourse. The water authorities currently dispose of about 1.3 million tonnes dry solids of sludge each year (1977 figure, DOE/NWC 1978) at a cost of about £50 million (Coker, pers.comm.). The Report of the Sub-Committee on the Disposal of Sewage Sludge to Land (DOE/NWC 1981) states: 'It is incumbent on water authorities to dispose of sewage sludge at the lowest cost compatible with the avoidance of harm or nuisance'. The cost of the disposal of sludge to agricultural land often compares favourably with other methods (eg land fill, incineration) and about 44% of UK sludge is disposed of in this manner (DOE/NWC, 1978).

There was an early recognition of the fertilizer value of sludges (Royal Commission on Sewage Disposal, 1908) which led to their extensive use for crop production, often on land dedicated for this purpose (ie sewage farms). In recent years the increase in the volume of sludge produced and the realization that repeated, heavy application of sludge can lead to an undesirable accumulation of potentially toxic elements (PTE's) has encouraged the water authorities to promote the use of sludge on private agricultural land. Grassland is considered particularly suitable for this purpose because it is accessible for most or all of the year, thereby reducing the need to provide alternative disposal methods or storage.

1.2 Types of sludge applied to grassland

There are a variety of methods of treating sewage and these give rise to differences in value and suitability of the resultant sludges as grassland fertilizers. For this reason it is necessary to briefly review the various sewage treatment processes and the nature of the sludges produced. This has been adapted from DOE/NWC (1977).

Sewage entering the works is screened to remove coarse organic solids. These may be macerated and returned to the sewage flow. Grit is removed by sedimentation. The effluent passes to a primary sedimentation tank where the large solids (60-70% of the total suspended solids) are removed to form a liquid primary sludge (LPS). The LPS's are thick, odorous liquids with a relatively high fat and grease content (see Table 1). The organic fraction is derived from plant and animal material undigested by the human gut plus the waste from domestic and commercial food preparation.

Table 1 The Proximate Composition of Different Types of Sewage Sludge

Component	Sludge Type		
	LPS	LAS	LDS
	% Dry Solids		
Fat (Ether Extractable)	7-35	5-12	3.5-17
Hemicellulose	3.2		1.6
Cellulose	3.8	7.0	0.6
Lignin	5.8		8.4
Protein	22-28	37.5	16-21

After Galwardi et al. (1974)

Effluent from the primary treatment process passes to a secondary (aerobic) treatment process where the lighter suspended organic matter and organic matter in solution is oxidized by micro-organisms held on an inert medium in percolating beds or within floc in aerated tanks. Surplus microbial biomass plus some untreated material is removed as a liquid humus sludge from the percolating beds or as liquid activated sludge (LAS) from the aerated tanks. The proportion of microbial biomass to untreated material is determined by the design and retention time of the treatment process. Aerobic sludges have a lower fat and grease content and a higher protein content than that of primary sludges (Table 1). Some works recycle the secondary sludge to the primary sedimentation tank to produce a co-settled sludge.

Larger sewage treatment works (STW's) commonly anaerobically digest a co-settled sludge either at atmospheric temperature in open tanks or at about 35°C in closed vessels. During anaerobic digestion about 35% of the sludge solid is liberated as CO_2 and CH_4 and much of the N is brought into solution as NH_4^+- N. The result is a liquid digested sludge (LDS).

Many works employ air-drying or mechanical dewatering of sludges to a solid before disposal. Mechanical dewatering is not economical unless the sludge is conditioned with a flocculating agent such as lime, aluminium chlorohydrate, ferric sulphate, ferric chloride or a polyelectrolyte. The characteristics of the sludge produced depend on the type of liquid sludge dewatered, the conditioner used, the method of dewatering or drying and the length of storage time.

1.3 The role of sludges as fertilizers in grassland farming

To appreciate the factors which determine the value of sludge to the grassland farmer it is necessary to understand the role of fertilizers in modern grassland farming.

Fertilizers are added to the soil to relieve a nutrient deficiency or to prevent a deficiency occurring by replacing nutrients removed in grass crops or by soil processes and not returned in manure.

Most soil under lowland pure grass swards are deficient in N. Morrison et al. (1980) found a linear dry matter (DM) yield response to applied inorganic N up to 300 to 350 kg N ha^{-1} yr^{-1} at 21 sites distributed throughout the UK. The DM yield response by grass/clover swards to applied N is much smaller than that of a pure grass sward, as the clover growth is suppressed by the increased grass growth (Cooke, 1975).

A DM yield response to K fertilizers may be obtained on many soils, particularly where large crops have been removed and no maintenance K applied (Whitehead, 1970). Cooke (1975) suggested K fertilizer should be applied to most soils to replace losses unless soil reserves were large.

Whitehead (1970) considered P deficiencies to be less common than those of K. Repeated applications of P fertilizer to lowland swards have built up P reserves in many soils (Sluijsman, 1981) but it is important that these reserves are maintained by redressing losses of P with applications of fertilizer.

The Ca, Mg and micronutrient concentrations in the soil are rarely low enough for there to be a DM yield response to their addition in fertilizer but it is not unusual for concentrations in herbage to fall below those required for good animal nutrition (Cooke, 1975, Osbourne, 1980).

The large response of DM yield to applications of N gives the farmer a measure of control over the production of grass. By varying the amount and timing of the application of N the growth of grass can, to a limited extent, be managed according to the demand for grazing or grass for conservation.

Sludges contain potentially valuable concentrations of N and P but little K (Table 2). The Ca, Mg and organic matter in sludges may also be of some value (Coker, 1979). The monetary value of the P in sludge is greater than that of the N and this led Hinnesley et al. (1971) to suggest that sludges should be considered primarily as P fertilizers. However the maintenance P requirement of most grassland is small as most of the P removed in cut or grazed grass is returned in the animal manure (Cooke, 1975). Consequently it is the sludge N which is of greatest value to the grassland farmer. If this N is to be used to assist in the management of grass production, the supply of sludge must be dependable and the response to its application rapid and effective.

1.4 The current situation

Sludges are usually supplied to the farmer without charge although some water authorities charge for transportation. The sludge application rate is varied according to the farmer's requirements and is calculated on the basis of the analysis of a bulked sludge sample taken over several weeks or months. Liquid sludges are normally applied to grassland by 4 wheel drive tanker or by farm machinery designed for slurry spreading. Solid sludges are usually applied by the farmer using a muck spreader.

It is usually uneconomical to transport sludge over long distances so most sludges are applied to farms within a short distance of the STW's. As most of the major towns in the UK are situated in lowland areas, it is probable that most sludges are applied to lowland farms.

Guidance for the application of sludges to agricultural land is given by the Department of the Environment (DOE) in conjunction with the National Water Council (NWC) and by the Agricultural Development and Advisory Service (ADAS). The guidelines give advice concerning the fertilizer value of sludges and make recommendations for precautions to be taken to reduce the risk to plants, animals and man from sludge-borne

Table 2 The Composition of LPS, LAS, LDS and Solid Sludges

Component	LPS		LAS		LDS		Solid Sludge	
	Range	Com	Range	Com	Range	Com	Range	Com
Solids	5-12		0.8-5.4	2.3	0.9-11.0	5.0	14-40	32
					% dry solids			
Loss on Ignition	60-80		60-80	65	36-62	48	19-73	51
Organic C			15-40	30	18-39	27	-	
Total C	34-46		36-43	-	20-31	26	-	
Inorganic N	0.3-0.7		0.12-2.6	0.4	0.5-4.8	2.0	0-0.6	
Exchangeable NH_4 - N % total NH_4^+- N	-		-		5-20		-	
C:N	7.5-15.5	9.0	4.6-9.9	6.0	1.9-7.5	5.0	8.0-27.4	
Total N	2.5-4.5	3.5	3.2-7.0	5.5	2.3-9.7	3.8	0.6-4.2	
P	0.5-1.5	1.0	1.1-5.5	2.7	0.5-14.3	3.0	0.4-6.9	
K	-	0.4	0.08-1.4	0.4	0.02-2.6	0.3	0.04-0.7	
Ca	-	1.9	0.6-13.5	3.0	1.9-20.0	4.9	0.8-1.6	
Mg	-	0.4	0.03-1.1	0.41	0.03-1.9	0.48	0.1-1.1	
Al	-	1.1	0.1-2.3	0.4	0.1-13.5	0.5	-	
					$mg\ kg^{-1}$ dry solids			
B	-		17-74	33	12-760	36	-	
Cd	2- 25		5-2170	16	3-3410	16	1-2615	
Cr	5- 375		10-13600	260	24-28850	1350	8-202	
Co	-		-	-	3-18	7	-	
Ca	93- 575		85-2900	970	85-10100	1000	59-1130	
Pb	12 - 400		13-15000	300	58-19730	540	81-500	
Mn	-	200	55-1120	340	58-7100	280	-	
Hg	0.7-3		1-22	5	0.5-10600	5	-	
Mo	-		2-60	30	24-30	30	-	
Ni	50- 125		2-1700	31	2-3510	85	3-120	
Zn	350- 975		108-14900	1800	108-27800	1890	196-1471	
pH	-		6.5-7.7		6.9-7.9		5.3-12.7	

Com - Common. Value not quoted if insufficient analyses found

Sources of analyses: Rodulf and Gehm (1942), Barrow (1955), Hinesley and Sosewitz (1969), King and Morris (1972), El Bassam and Tietjen (1974), King et al (1974), Ryan and Keeney (1975), Stewart et al (1975 b), Burns and Boswell (1976), Cornfield et al (1976), Furr et al (1976), Morel and Jacquin (1976), Sommers et al (1976), Magdoff and Chromec (1977), Sommers (1977), Beauchamp et al (1978), Coker (1978), DOE/NWC (1978), Epstein et al (1978), Damgaard-Larsen et al (1979), Mitchell et al (1980), Hsieh et al (1981), Chapman (pers. comm.), Coker (pers. comm.)

pathogens and PTE's. Each water authority formulates its own code of practice for the application of sludge to agricultural land with reference to the DOE/NWC guidelines and according to the demands of the local conditions.

The estimates of the availability of sludge N suggested in the DOE/NWC and ADAS guidelines that were operative at the inception of this investigation (DOE/NWC, 1977, ADAS, 1978) were based upon the work of Coker (1966 a to c) on the use of LDS on grassland and the investigations at Rothamsted into the use of solid sludges in arable farming (Bunting, 1963). Whilst the results of these investigations are very useful, they do not alone provide an adequate basis for giving advice on the availability of sludge N to grass. The current guidelines (DOE/NWC, 1981) recognised this lack of information but still based recommendations on the results of a small number of investigations. Neither the 1977 nor the 1981 guidelines considered the effect of sludge applications on the quality of grass produced or examined in detail the manner in which sludge applications could be integrated into the grassland farming system. This investigation was therefore undertaken in the expectation that the results obtained, in conjunction with those obtained by other workers, would enable the advice given by the DOE and by ADAS to be extended and consolidated.

1.5 Approach and objectives

At the inception of this investigation a recent review of the literature concerning the performance of sludges as N fertilizers for grassland was not available. Such a review was therefore undertaken (Chapter 2). One of the conclusions of the review was that with the exception of Coker's investigations with LDS (Coker, 1966a to c), the use of sludges as N fertilizers for grassland in the UK had not been examined in the field. Field experiments were therefore designed to determine:-

1) The availability of the N in various types of sludge when applied to grassland.

2) The quantity and quality of herbage produced by sludge applications.

3) The reliability of the sludges as tools for the management of herbage production.

4) The consequences of the use of sludges as N fertilizers on soil properties.

The performance of the sludges was compared to that of inorganic N fertilizer as this was considered the basis on which most farmers would evaluate the sludges.

The results of these experiments were compared to those obtained by other investigations to assess the current and future value of sludges to grassland farmers and to recommend ways in which this value could be maintained or improved.

Although grassland includes land carrying both pure grass and grass/clover swards, it was felt that the clover content of most lowland swards was too low to warrant a detailed examination of the response of grass/clover swards to sludge applications. However it was considered likely that clover could still be making an important contribution to herbage production on individual farms. Consequently the DM yield response of grass/clover swards to sludge applications was examined (Chapter 8).

CHAPTER 2

REVIEW OF THE LITERATURE

This review was initially undertaken to assess the performance and reliability of sludges as N fertilizers for grassland from the reports of previous investigations and to identify topics which required further research. In the four years since the review was undertaken the results of many investigations relating to the value of sludges as fertilizers have been reported. These results are complementary to rather than duplications of this investigation. They have therefore been incorporated in this review of the literature to give an account of the current state of knowledge.

2.1 The composition of sludge

The following review was undertaken to:-

1) Illustrate the differences between sludge types.

2) To determine whether the composition of a sludge used for experimentation was representative of that sludge type.

3) To determine the range of sludge compositions over which any recommendations are likely to be applied.

4) To assess the contribution of variations in the composition of a sludge to variations in crop response to sludge applications.

2.1.1 Differences between sludge types

Table 2 was constructed from analyses which have appeared in the literature. The greatest amount of information was available concerning the composition of LDS and the least concerning the composition of LPS and solid sludges. The analyses of LAS and solid sludges were taken from investigations into their value as fertilizers so are unlikely to represent the full range of concentrations of elements which may occur.

The differences between the sludge types were small in comparison with the wide range of concentration of elements found within each type. The LPS has a lower P concentration and higher C:N ratio than the other liquid sludges. The LAS has the highest N concentration but the lowest solids concentration. The loss on ignition (= organic matter) is lowest in the LDS due to the destruction of organic matter during digestion. The loss of C as CO_2 and CH_4 leads to a narrowing of the C:N ratio whilst the decomposition of protein during digestion liberates much of the N as NH_4^+- N and leads to a rise in sludge pH. The concentration of PTE's expressed as dry solids is highest in LDS. Some elevation of PTE's concentration in LDS would be expected due to the reduction in the dry solids concentration through the destruction of organic matter. However, part of the difference in PTE concentration between LDS and the other sludges is probably due to the extensive use of digestion at larger STW's where the amount of industrial effluent is substantial and to the source of the information used to construct Table 2 (p 8). The composition of solid sludges depends upon the composition of the liquid sludge dewatered. Solid sludges derived from LPS or LAS are similar in composition to the parent material although the addition of conditioners can increase the concentration of Al or Fe and where lime is used the sludge pH and Ca concentration are elevated. The dewatering of LDS leads to the loss of much of the NH_4^+- N in the liquor and consequently the C:N ratio is considerably widened.

2.1.2 Variation in composition between sewage treatment works

The variation in the composition of LDS's between STW's has been investigated by Sommers et al. (1976). The greatest variation was in the concentration of inorganic N and some PTE's (Table 3). The high variation of the inorganic N concentration may in part have been an artifact created by expressing the concentration on the dry solids content of the sludge as the concentration of NH_4^+- N (>90% of the

Table 3 The Variation in the Chemical Composition of Sewage Sludge between and within STW's

Component	Between City STW's	Within City STW's	Within a Rural STW
		CV%	
Solids	56	53	-
Inorganic C	54	20	-
Organic C	13	17	12
$NH_4^+ - N$	160	82	12
$(NO_3^- + NO_2) - N$			66
Organic N	42	23	-
Total N	-	-	-
Inorganic P	26	25	12
Organic P	52	95	
K	83	39	30
Ca	40	20	14
Mg	32	25	22
Cd	130	72	-
Zn	77	41	14
Cu	104	48	10
Ni	146	45	-
Pb	122	22	-
Source	Sommers et al (1976)		Kelling et al (1977)

CV - Coefficient of variation

inorganic N) in wet sludge was generally within the range 200-500 mg l^{-1}.

The variation in the composition of other sludge types between STW's has not been investigated.

The source of the variation in the composition of LDS between STW's can be attributed to differences in the initial composition of the sewage and in the treatment process. Sommers et al. (1976) found the presence of industrial effluent in the sewage entering some STW's positively skewed the distribution of concentration of PTE in digested sludge. The same authors noted that differences in the mixture of sludges digested may explain some of this variation. A marked variation between STW's in the performance of sludge digesters has been reported (Swanwick et al., 1969, Montieth and Stevenson, 1980, Brade and Noone, 1981). Inadequate mixing within certain reactors was found to reduce the actual sludge retention time substantially below the theoretical retention time. Inadequate mixing may lead to variable amounts of untreated sludge appearing at the digestion outflow.

2.1.2 Variation in the composition within a sewage treatment works

The variation in the composition of LDS from the same STW over time has been found to be considerable (Sommers et al., 1976, Doty et al., 1977, Kelling et al., 1977, Morel et al., 1978, Heck et al., 1978, Keller, 1979, Wong and Yip, 1980, Beckett, 1980) and sometimes to be as large or larger than that between STW's (Table 3). The highest variation was in the concentration of inorganic N and some PTE's. The variation was found to be decreased by treatments which mix the sewage or sludges over a period of time (Beckett, 1980) or which increase the solids content of the sludge (Doty et al., 1977). Periodic discharges from industrial sources were found to increase the variation and impart a positive skewness to the distribution of PTE concentrations over time (Sommers et al., 1976, Beckett, 1980). The magnitude of the increase in variation due to the presence of industrial effluent can be seen by comparing the sludges of domestic and industrial origin in Table 3. Seasonal variation in the composition of sludges have been found by Morel et al. (1978), Wong and Yip (1980) and Keller (1979), but not by Hunter and Heukelekion (1965). Beckett (1980) found the composition of sewage to vary according to the day of the week. The composition of sewage was not found to be related to rainfall (Beckett, 1980) whereas both rainfall and temperature were found to affect the composition of sludge in drying beds (Wong and Yip, 1980).

2.1.4 Conclusion

The differences in composition between sludge types are small in comparison with the variation within a sludge type. The concentration of N is highest in the LAS but the concentration of inorganic N is highest in the LDS. The C:N ratio is lowest in the LDS and highest in the LPS and in solid sludges.

Variation in the composition of sludges of the same type between STW's are considerable due to differences in the composition of the raw sewage and in the treatment processes.

Variation in the composition of a sludge within a STW is also considerable due to changes in the composition of the raw sewage over time and instability in the treatment processes. This variability may reduce the reliability of the sludge as a N fertilizer if applications are based on the analysis of a bulked sample.

2.2 The availability of nitrogen in sludges applied to grassland

The effectiveness of the sludge as a N fertilizer is determined by the availability of the sludge N whilst variations in the availability and rate of release of sludge N affect its reliability as a management tool. As all sludges contain both inorganic and organic N fractions, the availability and rate of release of the N in the sludge is dependent upon the availability and rate of release of the N in these two fractions and the proportion of each fraction in the sludge.

The availability of the inorganic, organic and total sludge N is often estimated by comparison with inorganic N fertilizers. These are usually assumed to be 100% available. However, the loss of N by volatilization from inorganic fertilizer containing NH_4^+- N or by leaching or denitrification from inorganic fertilizer containing NO_3^-- N may reduce the actual availability (Whitehead, 1970, Hargrove et al, 1977) Consequently an estimate of the availability of sludge N may vary depending upon the composition of the inorganic fertilizer 'standard' used. In considering the literature related to the availability of sludge N, this author has made the conventional assumption that inorganic fertilizer N is 100% available but accepts that some of the variability in the estimated availability of the inorganic, organic or total sludge N may be due to the use of different inorganic N fertilizers in the investigations quoted.

2.2.1 The availability of sludge inorganic nitrogen

The inorganic N in sludges (mainly NH_4^+-N) is readily absorbed by the grass either as NH_4^+-N or, following nitrification, as NO_3^--N. However NH_4^+- N may be lost from the soil by volatilization of NH_3 immediately after sludge application. The amount of NH_4^+ - N lost by volatilization as measured by incubation experiments was found to range from 4–6% (Premi and Cornfield, 1972) to <1% (Ryan et al., 1973, Sommers et al., 1979) in the absence of air movement over the soil but to be 11–60% (Ryan and Keeney, 1975) or 25% (Terry et al., 1978) in the presence of an air flow. Field measurements of NH_3 flux taken near stored or land-spread cattle manure have detected large NH_3 losses (Elliott et al., 1971, Luebs et al., 1973, Lauer et al., 1976). A low recovery of N led Coker (1979) to estimate a loss of about 70% of applied NH_4^+- N when LDS was applied to bare ground and allowed to dry. Field measurements by Beauchamp et al. (1978) detected losses of about 60% of the NH_4^+ - N applied in LDS surface-spread onto ploughed land in May and October. The rate of volatilization was found to decrease exponentially, giving a 'half life' of the NH_3 lost of 3.6 d and 5.0 d in May and October respectively. Furrer and Bolliger (1978) applied several types of sludge to grass in the glasshouse and found the response of N yield was closely related to the proportion of total sludge N present as NH_4^+- N. By extrapolating the relationship to 100% NH_4^+- N they found the availability of the NH_4^+- N in the sludge to be about 100% at pH

5.4-6.4. In a recent publication by Edgar et al. (1981) the results of applying LDS's containing varying proportions of NH_4^+- N to grass in the field are reported. The results of this investigation have been analysed by linear regression by this author (Fig 1). The extrapolation of the relationship to 100% NH_4^+- N shows the availability of the NH_4^+ - N in the sludge to be slightly greater than that in inorganic N fertilizer.

Terman (1979) concluded that the volatilization of NH_3 from sludges applied to moist soils increases with the intensity of drying conditions (higher temperature, wind speed and lower humidity) and with decreases in the soil sorption capacity for NH_4^+- N (coarser texture, lower CEC, higher pH and lower water content). High sludge solid contents may also increase the loss of N by volatilization (Edgar, 1981). Coker (1979) suggested NH_3 volatilization is negligible when sludges are applied to crops giving complete ground cover. Grass stubble might be expected to reduce NH_3 losses by reducing the evaporation of water from the sludge or by absorbing NH_3. A reduction in the loss of NH_3 from sludge due to the presence of grass stubble has been observed in the laboratory (Thomas, 1981).

The nitrification of NH_4^+- N to NO_3^-- N reduces the loss of N by volatilization. Nitrification of NH_4^+- N applied in sludges was found to occur rapidly when sludges and soils were mixed in incubation experiments (Premi and Cornfield, 1969, Stewart et al., 1975 b). Nitrification of NH_4^+- N held on the sludge CEC was slower than that from the liquid fraction (Stewart et al., 1975 b). Wilson (1977) concluded that the concentration and availability to micro-organisms of PTE's normally found in sludges of a domestic origin is unlikely to reduce the nitrification rate.

English et al. (1980) developed a model to describe the volatilization of NH_3 from sludges. The modelwas based on the results of a laboratory experiment and has yet to be tested in the field.

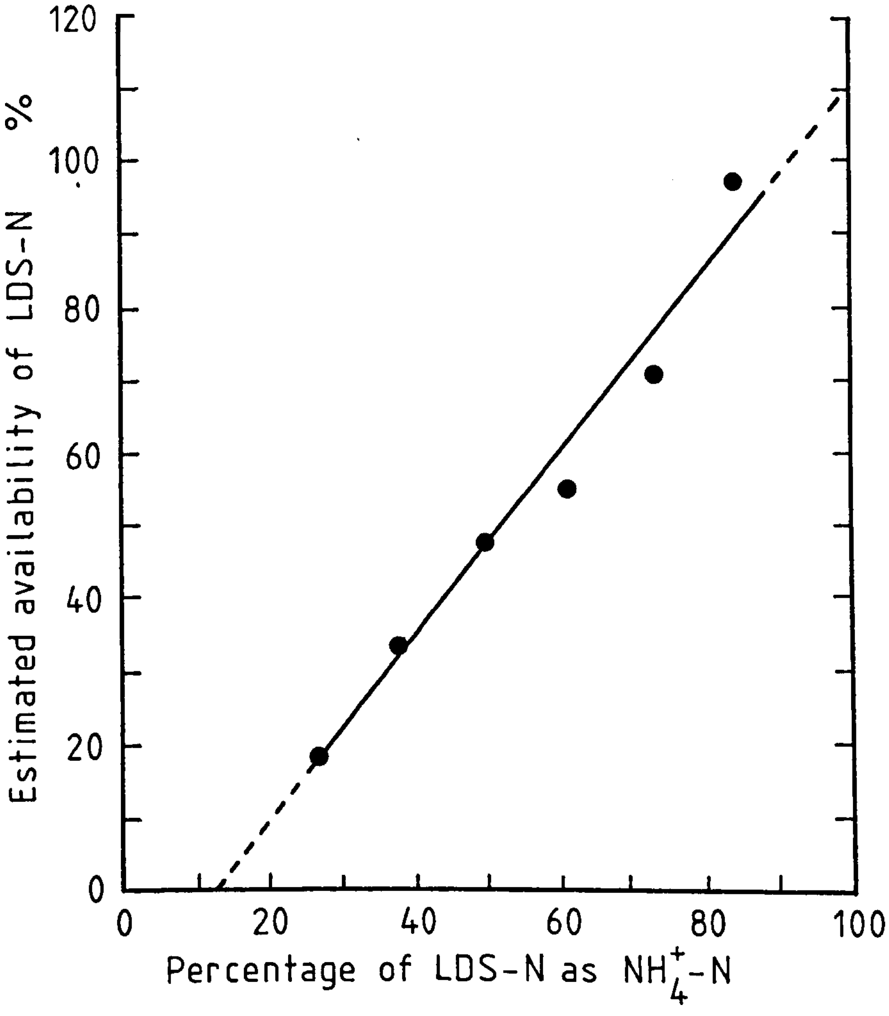


Fig 1 The regression of the estimated availability of LDS-N on the percentage of that N present as NH_4^+-N, calculated from Edgar et al (1981).

Most of the available N in grassland soils (including that applied in fertilizers) is found near the soil surface. Under drought conditions a lack of water near the soil surface was found to reduce the adsorption of available N, even though the grass was adequately supplied with water from further down the soil profile (Garwood and Williams, 1967a and b). Partial or complete irrigation was found to increase N yield under these conditions (Garwood and Tyson, 1973, Garwood et al, 1980). Coker (1979) suggested that although the amount of water applied in LDS is usually small in comparison with the water requirement of the sward, it may sufficiently moisten the soil to permit the uptake of the LDS NH_4^+-N and inorganic soil N. Tunney (1976) reported such an effect of cow slurry.

2.2.2 The availability of sludge organic nitrogen

Sludge organic N is not available for absorption by grass until it has been mineralized by micro-organisms. The amount of the organic N which becomes available to the grass depends upon the availability of the organic N to microbial attack and on the amount of mineralized organic N which is re-immobilized by the micro-organisms. For the purpose of this investigation, rapidly mineralized organic N was considered to be 'available'.

Several authors have measured CO_2 evolution and net mineralization rates in incubation experiments to investigate the biodegradability of sludge organic matter and to estimate the availability of organic N (Table 4). The results of these studies suggest that a substantial part of the organic matter in all sludge types is biodegradable. Although there is a wide range of reported values for the evolution of CO_2 and net mineralization of organic N within each sludge type, it is possible to distinguish the general features of each sludge type.

The evolution of LDS C as CO_2 was lower than that of the LAS C. This is probably due to the loss of C available to micro-organisms during digestion. The results of the incubation studies suggest that dewatering

Table 4 Net Carbon and Nitrogen mineralization from the organic fraction of liquid and Solid Sludge as determined in Incubation Experiments

Sludge	State of Sludge	Duration of Incubation days	Temperature of Incubation °C	Sludge Carbon Evolved %	Net Sludge Organic N Mineralized *** %	Source
			LIQUID SLUDGES			
P	L	56	20	39	7	Chaussod (1979)
AS	L	56	20	57	51, 23.5	Chaussod (1979)
AS	D	61	22	26	31 *	Hsieh et al. (1981 a)
AS	L	91	17		51	Magdoff and Chromec (1977)
AS	L	376	22	50–95	36–50**	Sommers et al. (1979)
AS	L	119	25		54	Magdoff and Anadon (1980)
AS	L	21	28	25		Morel and Jacquin (1976)
DS	L1	126	22		39	King (1973)
DS	L2	126	22		41	King (1973)
DS	D	168	21	-	40	Terry et al. (1981)
DS	D	61	22	8	29	Hsieh et al. (1981 a)
DS	D	105	35		41	Epstein et al. (1978)
DS	L	112	23		29–32	Beauchamp et al. (1979)
DS	L	376	22	24	0–11 *	Sommers et al. (1979)
DS	L	112			20–48	Ryan et al. (1973)
DS	D	183	Variable	20		Miller (1974)
DS	L	21	28	10		Morel and Jacquin (1976)
			SOLID SLUDGES			
DS		162	13–26	28–36		Mitchell et al. (1978)
DS		21	28	21		Morel and Jacquin (1976)
DS		367		29		Agbim et al. (1977)
DS		112			20–25	Anderson (1955)
DS		42	30		4	Premi and Cornfield (1972)
DS		91	17		21	Magdoff and Chromec (1977)
DS		56	20	3	11	Chaussod (1979)
AS		21	28	14		Morel and Jacquin (1976)

P Primary sludge DS Digested sludge AS Activated sludge

* Denitrification suspected

** High NH_4^+– N content suggesting partial auto-digestion

*** Where necessary, net organic N mineralization has been calculated from the author's data.

1 Surface applied D Sludge dried before incubation

2 Incorporated with soil L Liquid sludge incubated

does not have a great effect on the biodegradability of the sludge organic matter unless drying is vigorous (eg as reported by Premi and Cornfield, 1972) or conditions are favourable for decomposition (as in drying beds). The liming of a sludge was not found to retard sludge organic matter decomposition provided the rate of application of sludge to the soil was low (Morel and Jacquin, 1976, Chaussod, 1978).

The greater net mineralization of LAS organic N than LDS organic N would be expected given the difference in the C:N ratio (Table 2). However this may be somewhat fortuitous as there are probably considerable differences between the biodegradabilities of the organic matter in the two sludge types. The LAS organic N is derived from microbial floc and would be expected to be readily biodegradable. In contrast, the LDS organic N contains a large proportion of material which has resisted digestion plus microbial waste products. Both are likely to resist further microbial attack. Consequently, a much greater proportion of the LAS than the LDS organic N is probably mineralized. However, because the availability of LAS C to micro-organisms is higher than that of the LDS C, a greater proportion of the mineralized LAS organic N is likely to be re-immobilized. Epstein et al. (1978) found a much greater immobilization of mineral N in soil receiving raw sludge than in soil receiving LDS.

The effects of dewatering on the availability of the sludge organic N are probably similar to the effects on sludge organic matter biodegradability described above. The C:N ratio of some dewatered co-settled sludges may be sufficiently wide to produce temporary net immobilization of mineral N. Temporary net immobilization was found when LPS or co-settled sludges with a C:N ratio of >15 were applied to the soil (Chaussod, 1978).

Several authors have estimated the availability of the organic N fraction of sludges from the results of field trials. A method adopted recently by Magdoff and Amadon (1980) makes the assumptions that no NH_4^+- N is lost from the sludge by volatilization and that mineral N derived from the inorganic or organic N fractions of the sludge is absorbed by the plant as efficiently as that derived from inorganic N fertilizer. The proportion of the whole sludge effect due to the NH_4^+- N fraction is then calculated from a knowledge of the composition of the sludge. The residual effect is then attributed to the action of the organic N.

Using the above method Magdoff and Amadon (1980) calculated the availability of LAS organic N to be 55% in the first year. The availability of the organic N in LDS during the first year after application has been estimated as 20% by Edgar et al. (1981) and <10% by Thomas (1981).

The method of determining the availability of NH_4^+- N described by Furrer and Bolliger (1978, p 13) can also be used to estimate the availability of the sludge organic N by extrapolating the relationship to 0% NH_4^+- N (100% organic N). These authors did not distinguish between sludge types when determining the relationship between the response of N yield and the proportion of total N present as NH_4^+- N so the availability of the organic N calculated (25%) does not distinguish between sludge type. Eight of the sludges tested were LDS's so the relationship has been recalculated by this author to obtain an estimate of 27% for the availability of LDS organic N (Fig2). If this method is used on the results given by Edgar et al. (1981) a negative value for the availability of the LDS organic N is obtained (Fig 1). The authors attributed the poorer response to NH_4^+- N with increasing organic N content to an increase in volatilization of NH_3 as the solids concentration increased (0.3% dry solids at 84% NH_4^+- N, 6.0% dry solids at 26% NH_4^+- N)

The course of the decomposition of LAS and LDS solids over time has been followed by monitoring CO_2 evolution in incubation experiments.

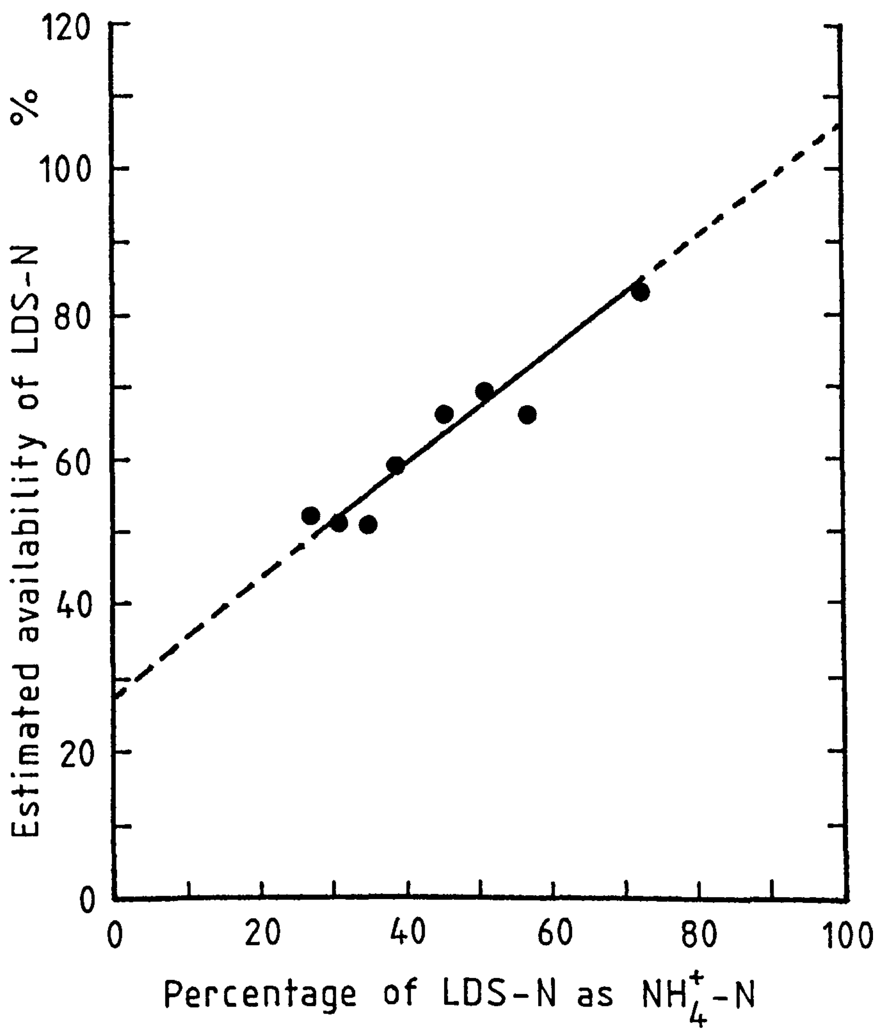


Fig 2 The regression of the estimated availability of LDS-N on the percentage of that N present as NH_4^+-N, recalculated from Furrer and Bolliger (1978).

It was found to be described by an exponential decay function (Hsieh et al., 1981a) or alternatively a composite function assuming the existence of rapidly and slowly decomposable sludge organic fractions (Gilmour and Gilmour, 1980, Reddy et al., 1980).

The decomposition of sludge organic matter was found to be sensitive to changes in relatively few environmental factors. Incorporation into the soil was found to reduce CO_2 evolution (Terry et al., 1979) but have little effect on net N mineralization (King, 1973). Increasing soil temperature in the range 5 to 35°C was found to increase the rate of decomposition (Miller, 1974, Terry et al., 1979, Hsieh et al., 1981 a). The same authors found little effect of soil moisture on decomposition rate though Miller (1974) and Schaumberg et al. (1980) found the decomposition rate to be slowed or stopped under saturated conditions. Miller (1974) found the effect of saturation to increase as the clay content of the soil increased. The range of soil moisture tested may not extend down to the levels which can occur near the soil surface during prolonged dry periods. Other soil environmental factors such as pH, organic matter and clay content (under non-saturated conditions) have not been found to influence the decomposition of sludges (Glathe and Malakawi, 1963, Miller, 1974, Furrer and Bolliger, 1978, Sommers et al., 1979). This is in contrast to the negative effect of decreasing pH observed on the mineralization of soil N (Cornfield, 1959) and to the protection against microbial attack which can be afforded to organic matter when associated with certain types of clay (Lynch and Cotnoir, 1956, Bremner, 1965, Guckert et al., 1976).

The supply of a readily biodegradable C source plus the blockage of soil pores with sludge organic matter may lead to the development of anaerobic conditions and a loss of N by denitrification. This was observed frequently in incubation experiments where sludge application rates were often high and soil aeration inadequate (eg King, 1973, Ryan et al., 1973). The larger amount of readily biodegradable organic matter in the LAS may be of significance in this respect (Epstein et al., 1978). Denitrification of sludge N is unlikely to occur unless anaerobic conditions develop some time after sludge application or unless aerobic and anaerobic zones exist simultaneously in the same soil. This is because there is little NO_3^- - N in most sludges, and organic N and NH_4^+- N in sludges must be nitrified before denitrification can take place. The denitrification of existing soil or fertilizer NO_3^- - N is more likely.

2.2.3 The availability of the total sludge nitrogen

The amount of mineral N in most LAS's is quite small (Table 2) so the availability of the total LAS N would be expected to be largely determined by the availability of the organic N. The results of pot and field trials (Table 5) are similar to those obtained for LAS organic N in incubation experiments and suggest that the availability of LAS N is between 40 to 70% in the first season after application.

The proportion of NH_4^+- N to organic N in LDS's from different STW's or the same STW over time was found to vary considerably (p 9) Given the large difference in the availability of the NH_4^+- N and organic N fractions (see above), the wide range of estimates of the availability of the total LDS N found by pot and field trials is to be expected. Coker (1979) suggested the availability of LDS N could be predicted from the formula 100% x NH_4^+- N + 17% x organic N whilst Furrer and Bolliger (1978) suggested 90% x NH_4^+- N + 25% x organic N. No one formula has gained widespread acceptance.

No reports of the availability of dewatered, co-settled sludge N to grass were found. Field trials on arable crops suggest the availability may be about 30% (Bunting, 1963, Garner, 1966). These sludges contain little inorganic N (Table 2) and the biodegradable C: biodegradable N ratio is probably high (p 16) so much of the N is likely

Table 5 The Availability of the Nitrogen in Sewage Sludges as determined by Pot and Field Trials

Sludge	Parameter Measured	Experiment Type	Estimated Plant Availability of Sludge N %	Source
AS	N	Pot	48	Furrer and Bolliger (1978)
AS	N	Pot	43	Furrer and Bolliger (1978)
AS	DM	Pot	60-100	O'Riordan (pers. comm.)
AS	DM	Field	35-50	O'Riordan (pers. comm.)
AS	DM	Field	65	Magdoff and Amadon (1980)
AS	DM	Pot	66	Brenchley and Richards (1920)
DS	DM	Field	20-45	O'Riordan (1979)
DS	N	Field	85	Coker (1979)
DS	N	Field	45, 100	Debruck (1977)
DS		Field	42	Suess (1979)
DS			40-50	Keller (1978)
DS	N	Pot	20-80	Furrer and Bolliger (1978)
DS	N	Field	70	Thomas (1981)
SOLID SLUDGES				
DS	N	Field	30	Larsen (1979)
DS	N	Pot	32	Furrer and Bolliger (1978)
DS	N	Pot	37	Furrer and Bolliger (1978)
DS	DM	Pot	12	Marks (1978)
DS			12-20	Coker (pers. comm.)

AS Activated sludge DS Digested sludge

The test crop was grass in all cases except Larsen (1979). The estimates obtained by Larsen have been included as N lost in drainage was measured and included in the calculation of sludge N availability.

to be immobilized during decomposition. Most of the available N in LDS is lost when the sludge is dewatered. The amount of NH_4^+- N left in the remaining water and on the sludge CEC has not been investigated. Analytical results given by Furrer and Bolliger (1978) suggest that up to 15% of the total N of a dewatered LDS may be present as NH_4^+- N. This may explain why the availability of the N in some dewatered LDS's as determined by pot and field trials is in excess of that which would be expected given the availability of the LDS organic N fraction (p 17)

The effect of environmental factors on the availability of sludge N has not been extensively investigated in pot or field experiments. Furrer and Bolliger (1978) found the availability of LDS N to grass in pots decreased as the soil pH increased. This was due to an increase in the volatilization of NH_3, the net mineralization of organic N was little affected. In contrast, Coker (1966a) found little difference between the response to LDS applied to grass/clover swards established on soils with differing soil type and pH.

2.2.4 The rate of release of sludge nitrogen

The speed at which sludge N becomes available to the grass has not been extensively investigated although several authors have commented upon the residual fertilizer value of sludge applications. Coker (1966 c) found LDS N was more rapidly absorbed by barley than inorganic fertilizer N. The same author has since reported the views of farmers that earlier spring grazing can be obtained by the use of LDS compared to inorganic N fertilizer (Coker, 1979). Thomas (1981) reported a rapid uptake of LDS N labelled with ^{15}N. Coker (1966b) examined the residual effects of two years applications of LDS and inorganic N fertilizer on the N yield in the year following the end of the applications. The residual fertilizer effect of the LDS N was greater than that of the inorganic fertilizer N but both were small in comparison with the responses obtained in the previous two years. In a later review this author considered that for practical purposes the residual effect of LDS N could be ignored (Coker, 1971). Magdoff and Amadon (1980) found a substantial residual effect on the DM yield of the first cut of the year following applications of LAS in the previous growth season. However, Stark and Clapp (1980) found little difference between the residual effects of LDS and LAS $2\frac{1}{2}$ years after the end of 3 years of heavy applications.

The slowness with which solid sludge N is released is widely recognised (Coker, 1971, DOE/NWC, 1981). Lunt (1959) found the N in a dried digested sludge to be only slowly nitrified. The same author also found a more rapid N release from a digested sludge which had been conditioned with $FeCl_3$ and lime then vacuum filtered than from one which had been air dried. Surface applied solid sludges have been observed to persist as discreet lumps on the soil surface for some time after application (Gregory and Harkness, 1979) so the rate at which N is released may be reduced by the inhibition of decomposition during dry periods.

The reports quoted above suggest the rate of release of N decreases in the order LDS > LAS > solid sludge and that the rate of release of LDS N may sometime be greater than that of inorganic N fertilizers. The variations in the proportion of organic and NH_4^+- N in LDS (p 9) and in the quality of the organic N in the solid sludges (p 16) suggests that there may be considerable variations in the rate of N release within these sludge types. The ranking described above may not therefore be valid in all circumstances.

2.2.5 Conclusion

There are marked differences between the availability of the inorganic and organic N within a sludge and between the availabilities of the organic N from different sludge types. The effect of changes in the environment on the availability of sludge N depends upon the type of sludge and the distribution of the N between the inorganic and organic forms.

This suggests that there are greater differences between and within sludge types than is recognised in the current guidelines (DOE/NWC, 1981) and that the reliability of sludge as N fertilizers may be reduced by variation in the availability of sludge N in response to changes in the environment.

The rate at which sludge N is released and becomes available to the grass usually decreases in the order LDS > LAS > solid sludge although it is probable that variation within sludge types, particularly the LDS and solid sludge, may lead to considerable overlap. There is limited evidence to suggest that initially the release of N from LDS may be faster than that from inorganic N fertilizers.

2.3 The effect of sludge application on grass DM yield, grass quality and soil fertility

The purpose of this review is to assess the likely response to sludge applications in the quantity and quality of grass produced and to determine the residual effect of sludge applications on soil fertility. Comparisons with inorganic N fertilizer are made where relevant.

2.3.1 Grass DM response

The DM yield response to an application of N fertilizer depends upon the amount of N which becomes available to the grass and the efficiency with which this is used to create DM. The factors affecting the recovery of inorganic and sludge N have been discussed in 2.2 The factors affecting the efficiency with which the N is used to create DM are discussed below.

Under conditions in which neither nutrient nor water were limiting, Anslow and Green (1967) found the greatest rate of DM increase to occur in spring when the grasses were in the reproductive growth stage. The rate then declined as the growing season progressed, growth ceasing in late November. Cooke (1975) considered the marginal response (kg DM kg^{-1} N applied) could be as much as 40 kg DM kg^{-1} N when inorganic N fertilizer is applied in late February or early March for hay or late silage. A response of 10 to 15 kg DM kg^{-1} N could be expected from inorganic N fertilizer applied for out of season grass.

Poor responses to applied N have been obtained following the removal of a large yield of grass, particularly when it was reproductive growth which had been removed. This was probably due to a reduction in tiller density (Whitehead, 1970).

The sward management has been found to have a large effect on the marginal response to fertilizer N. The marginal response tends to decrease as the frequency and severity of defoliation increases (Whitehead, 1970).

Morrison et al. (1980) found an inverse polynomial model gave the best description of the increase in DM in response to increasing inorganic N fertilizer application on 21 sites. The response was essentially linear over the range 0 to 300 kg N ha^{-1} yr^{-1} with a range of marginal responses from 14 to 29 kg DM kg^{-1} N. The efficiency with which the N taken up was used to create DM (E_N) decreased from a mean of 43 kg DM kg^{-1} N taken up at 0 kg applied N ha^{-1} yr^{-1} to 27 kg DM kg^{-1} N taken up at 750 kg applied N ha^{-1} yr^{-1}.

Brockman (1974) found the marginal response within a growth period was greatest if the N fertilizer was applied immediately after defoliation and that it decreased progressively the later the fertilizer was applied. He considered that the N should be applied within a week of defoliation if DM yield was not to be lost.

The response to N fertilizer applications in autumn or winter is restricted by low temperatures. Blackman (1936) found grass would not respond to fertilizer N if the 10 cm soil temperature was below 5.6°C. Whitehead (1970) concluded that low temperature restricted DM production in the early spring and that light intensity may be a limiting factor during dull weather in the summer. Morrison et al. (1980) found E_N to vary very little between 21 sites representing a wide range of soil and climatic types in the UK.

It is an assumption implicit in many investigations that the N absorbed by the grass from sludge is used as effectively to create DM as N absorbed from inorganic N fertilizer. As noted above, the value of E_N may fall if an application of inorganic N fertilizer is delayed for more than a week after defoliation. Since part or all of the N in sludges must be mineralized before absorption can occur, the release of N may be delayed sufficiently to reduce E_N. This would mean that the DM yield response to a given amount of sludge would be lower than to an application of inorganic N fertilizer supplying the same amount of available N.

2.3.2 Protein concentration in the grass

Protein is required by livestock as a source of energy and N. An adequate N supply in the diet is required to ensure good utilization of herbage carbohydrates by rumen bacteria (MAFF, 1975).

Protein in grass is usually calculated as crude protein (CP) from a knowledge of the N concentration in the plant. The equation assumes a concentration of 16% N in plant protein. The true protein N content of the plant is 70 to 90% of the total N, the remainder existing as peptides, amino acids, amines and NO_3^-- N (Osbourne, 1980). The normal range of CP concentrations in harvested grass is 6 to 30% (MAFF, 1975).

As the CP is calculated from the concentration of N, the effect of inorganic N fertilizer or sludge applications depends upon the increase in the amount of N in the grass divided by the increase in the amount of DM, ie CP is related to $^1/E_N$. This means that a given amount of sludge may increase the concentration of CP more than an application of inorganic N fertilizer supplying the same amount of available N (p 24).

2.3.3 Digestibility of the grass

The digestibility of the grass is the percentage which is digestible in the cow. The digestibility can be expressed as the percentage of DM digestible the percentage of the organic matter digestible. A common term in advisory work is D value, the digestible organic matter expressed as a percentage of the DM.

The livestock used in modern farming, particularly high performance livestock, demand a diet containing a large amount of metabolizable energy (ME). Digestibility is approximately related to ME by the equation ME = 0.15 D value (Osbourne, 1980), ie the higher the digestibility, the greater the ME content of the grass. The digestibility of grass is generally too low to supply sufficient energy to the livestock to maintain performance. The grass is therefore supplemented with a highly digestible feed (a concentrate). The cost of concentrates is high in comparison with the cost of the grass so the level of supplementation is adjusted according to the digestibility of the grass feed available with tables produced by MAFF (1975).

The following changes in the digestibility of grass over the season have been described by Osbourne (1980):

The digestibility of grass is determined by the proportion and digestibility of the cell contents and cell wall in the DM. The digestibility of the cell contents is about 100%. As a grass crop matures, the proportion of cell contents in DM decreases, the cell wall content increases and the digestibility of the cell wall fraction decreases. This leads to a reduction in the digestibility of the crop. This is particularly marked during the reproductive growth period since the stem of reproductive tillers contains a high content of lignified cell wall which has a low digestibility. The fall in the digestibility of regrowth is much slower than that of the reproductive growth due to the reduced amount of stem present.

The decline in digestibility of the reproductive growth coincides with the greatest increase in DM accumulation (Spedding and Diekmahns, 1972). Consequently there must be a compromise between the quantity and quality of grass cut. The date of first heading depends upon the species and variety of the grass, the day length and the weather. A production chart is produced by NIAB (1978) to enable farmers to make the compromise between the quantity and quality of the grass as they desire.

Whitehead (1970) concluded that N fertilization has little effect on the digestibility of a pure grass sward unless maturation is delayed or the supply of N from the soil is very low. Chestnutt et al. (1977) found N fertilization to have little effect on the digestibility of perennial ryegrass whereas Binnie et al. (1974) found it to reduce the digestibility of Italian ryegrass. Morrison et al. (1980) found there to be no consistent effect of N application on digestibility at the 21 sites over the 4 years of their experiment.

The digestibility of sludge treated herbage was investigated by Geering and Kunzli (1964) but the presence of clovers in the sward confounds any sludge effect. King and Morris (1972) studied the effect of large amounts of digested sludge on the digestibility of Coastal Bermuda grass. The digestibility of the grass from the control treatment was not given so it is not possible to determine if sludge increased or decreased digestibility. There was no change in the digestibility with increasing rate of sludge application and there was no difference between the digestibility of grass from sludge and NPK treated plots. This suggests that in this instance the sludge had no effect on the digestibility of the grass. Edgar et al. (1981) reported similar findings following the application of LDS at the rates normally used in the UK.

These reports suggest that the digestibility of the grass is as insensitive to applications of sludge as it is to applications of inorganic N fertilizer. The speed of the release of sludge N is therefore unlikely to affect grass digestibility.

2.3.4 Water soluble carbohydrate (WSC) concentration in grass

A level of more than 10% WSC in grass is required for satisfactory silage making without the aid of additives (NIAB, 1978).

The level of WSC in the grass is determined by the balance between photosynthesis and respiration. High light intensity increases photosynthesis and the level of WSC rises (Osbourne, 1980). Increasing temperature increases respiration so the WSC level falls. The application of N to a sward stimulates growth so reducing the concentration of WSC (Whitehead, 1970). Spedding and Diekmahns (1972) concluded that the WSC concentration in perennial ryegrass is considerably higher than in other species.

A slower release of N from the sludges than from inorganic N fertilizers (p 24) may lead to the supply of N to the grass receiving sludge being greater late in the growth period than the N supply to grass receiving N fertilizer supplying the same amount of available N. This may in turn lead to a stimulation of growth thereby depressing the concentration of WSC in the grass. The effect of sludge application on the concentration of WSC in grass has not previously been investigated.

2.3.5 Grass nitrate-nitrogen content

Excess NO_3^-- N in grass can lead to toxicity in livestock. The NO_3^-- N is reduced to NO_2^-- N which when absorbed into the blood stream converts haemoglobin into methaemoglobin which is unable to transport oxygen (Wright and Davison, 1964). These authors considered a NO_3^-- N concentration of greater than 0.4% in herbage DM to be potentially toxic. Whitehead (1970) quoted reports of higher concentrations of

NO_3^-- N being fed to livestock without deleterious effect. Deinium and Sibma (1980) considered a level of 1.2% NO_3^-- N to be the toxic threshold though an investigation by den Boer (1980) found no toxic effects in dairy cows fed fresh grass containing 3 to 4% NO_3^-- N. The type and rate of feeding may be important (Kemp, 1978).

The level of NO_3^-- N in grass rises when the rate of supply of NO_3^-- N from the soil exceeds the rate at which it can be reduced and assimilated. The reduction of NO_3^-- N requires energy and the NO_3^-- N content of grass has been related to the supply of WSC (Deinium and Sibma, 1980). The application of N fertilizers increases the supply of NO_3^-- N to the grass and can increase the concentration of NO_3^-- N in the crop. The concentration of NO_3^-- N in grass increases in a non-linear fashion as the rate of application of N is raised (Reid, 1966, Ennik et al., 1980).

A slower release of N from sludges than from inorganic N fertilizers (p 24) may lead to the supply of N to the grass late in the growth period being greater than that to grass receiving the same amount of available N in inorganic fertilizer. This may in turn lead to a higher concentration of NO_3^-- N in the grass than would have been expected from the amount of available N applied. This has not been investigated by previous authors although high NO_3^-- N concentrations were recorded in grass from a sewage farm (Rundle et al., 1981).

2.3.6 The Concentration of Potentially Toxic Elements in Grass and Soil

Sludges contain a range of PTE's at concentrations greatly in excess of those in most soils (Table 6). The consequences of the addition of sludge PTE's to the soil have been reviewed by Doyle et al. (1978) and DOE/NWC (1981) from which the following brief review is largely taken.

The low mobility of the PTE's in the soil means that repeated applications of sludges lead to an accumulation of PTE's. Sludges

Table 6 The concentration of PTE's in uncontaminated soils and plants

Element	Concentration mg kg^{-1} dry weight		
	soils		plants
	common	range	range
B	10	2 - 100	30 - 75
Cd	0.06	0.01- 7	0.2 - 0.8
Cr	100	5 - 3000	0.2 - 1.0
Cu	20	2 - 100	4 - 15
Pb	10	2 - 200	0.1 - 10
Ni	40	10 - 1000	1 - 10
Zn	50	10 - 300	15 - 200

Adapted from Richardson (1980)

applied to arable land are mixed with a large volume of soil during ploughing, reducing the PTE concentration by dilution. Much of the UK grassland is permanent or semi-permanent (Holmes, 1980) and so PTE's accumulate near the soil surface.

The PTE's differ in toxicity and mobility within the soil/plant/animal system. Pb and Cr are very immobile in the soil and are not normally taken up in large amounts by the plant, even when soil concentrations are elevated quite markedly. Zn, Ni and Cd are more readily absorbed by plants and may become phytotoxic. The movement of Cd up the food web to man is currently causing concern. Cu becomes phytotoxic if the concentration in plant tissue exceeds about 20 mg Cu kg^{-1} DM (Webber, 1980) though the Cu concentration in the aerial parts of plants is not readily increased by applications of Cu compounds to the soil. A concentration of 10 mg Cu kg^{-1} grass DM is recommended as the minimum necessary for good dairy cow nutrition (Osbourne, 1980) and Cu deficiency in animal diets is common (Anon, 1980). However a concentration in excess of 15 mg Cu kg^{-1} grass DM can lead to toxicity in sheep due to the interaction of Cu with other elements. Other animals are less sensitive to Cu.

Soil and plant properties are known to influence the absorption of PTE by plants. Since most PTE's carry a positive charge, their availability increases as the soil pH and CEC is lowered. Exceptions are organo - Cu complexes which increase in plant availability as the pH rises. Plant species differ in the amount of PTE absorbed under given soil conditions and the tissue concentration necessary to cause toxicity. Grasses are generally more tolerant of PTE's than arable crops, but clover was found to be sensitive (Davies, 1977).

The diet of grazing animals often contains 10% dry weight of soil (DOE/NWC, 1977). The consumption of PTE's by livestock, particularly PTE's which are not normally translocated by plants, may therefore be considerably increased by the uptake of sludge enriched soil. Some of the sludge applied to grassland is retained in the leaves. A field investigation by Chaney and Lloyd (1979) found the adherence of sludge PTE's to persist for several months after an application. The reduction in PTE levels was not related to rainfall and was not reduced by washing the leaves in detergent solution. This confirmed previous reports that sludge solids are held tenaciously by grass leaves if allowed to dry following the application (Chaney, 1976, Jones et al., 1979).

The guidelines for the use of sludges on land (DOE/NWC, 1981) contain recommended limits for the addition of PTE's to the soil which take into consideration soil type (calcareous or non-calcareous) and the background levels of PTE's . The phytotoxic effects of the elements Cu, Ni and Zn are considered to be additive according to the formula Zn + 2Cu + 8Ni. The product is termed the Zn equivalent and is also used to determine maximum permissible applications of sludge to land. The restrictions placed on the application of sludge PTE's to grassland are given in Appendix 1.

The applications of PTE permitted in the UK are generally higher than those elsewhere in Europe or in Scandinavia. Some countries reduce the permissible application of PTE's on grassland to one third of that permitted on arable land to reduce the accumulation of PTE's near the soil surface. Other countries dissuade or do not permit the use of sludge on grassland for hygienic reasons.

2.3.7 Soil Phosphate

The P content of sludges can be quite high (Table 2). This had led to the investigation of the use of sludges as P fertilizers. The immobility of P in the soil ensures a substantial residual effect of sludge P applications.

The assessment of the availability of sludge P to plants is less easy than for N as there is rarely a yield response to P application.

P recovery in harvested plant material and the P extractable with various chemicals have been used to estimate the availability of sludge P. The validity of both methods is still under debate (Hucker and Catroux, 1981).

A range of 20 to 100% sludge P availability in comparison to superphosphate was found by de Haan (1980). A similar range was reported in a review paper by Williams and Coker (1981). Coker (1980) found more P was extracted from liquid raw sludge than from LDS when mixed with three different soil types. Differences between the amount of P extractable from sludges treated with Ca, Al and Fe were reported by Soon et al. (1978), but no differences were found by Larsen (1981). The presence of PTE's may reduce the availability of sludge P (Pommel, 1981, Williams and Jones, 1981).

The wide range of values reported for the availability of the sludge P and the variety of factors found to affect it make it impossible to predict with accuracy the effect of the use of sludges as N fertilizer on the concentration of extractable P in the soil.

2.3.8 Grass calcium and soil pH

Ca is the dominant base which maintains soil pH against acidification. The Ca is held on the soil CEC but is displaced by such ions as K^+ and NH_4^+. If K^+ or NH_4^+ are added to the soil as the chloride or sulphate, the displaced Ca may be lost from the soil by leaching. This does not usually occur if the ions are added as the nitrate since the latter is absorbed by the grass. The nitrification of NH_4^+- N derived from fertilizers or the mineralization of organic N releases H^+ ions so increasing acidification.

Ca is also an essential nutrient for plants and animals. Milking cows require a Ca concentration in the diet of about 0.50% in DM (Osbourne, 1980).

Sludges commonly contain 3% to 5% Ca in dry solids (Table 2) so an application of 5 t ha^{-1} supplies about 150 to 250 kg ha^{-1} Ca. Sludges also contain NH_4^+- N and mineralizable N. The effect of the sludge on soil pH is therefore a balance between the supply of sludge Ca, the loss of Ca in the crop and the acidification due to the nitrification of sludge N.

The value of sludge Ca applied to grassland has not been extensively investigated. King and Morris (1972) found large applications of LDS depressed the exchangeable soil Ca and soil pH. The supply of N in their experiment was so high that substantial nitrification and NO_3^-- N leaching must have occurred. In addition, the low initial pH (5.2) and the poor Ca content of the sludge (1.5%) would have favoured the depletion of soil Ca. Soon et al. (1978) found applications of chemically treated sludges, particularly those treated with Ca, increased soil exchangeable and grass Ca concentrations. The increase in the grass Ca concentration due to the sludges was less than that due to NH_4NO_3 applications. The effect of the sludges on the soil pH was related to the available N to base (K+ Ca + Mg + Na) ratio. Large applications of sewage sludge to arable land were also found to increase soil exchangeable Ca and soil pH (Epstein et al., 1976).

These investigations suggest that the supply of sludge Ca is often greater than the depletion of Ca due to the activity of the sludge N. However a rise in soil pH is not inevitable as other factors (eg the mineralization of soil N) may also act to deplete the soil Ca reserve.

2.3.9 Grass and soil magnesium

A concentration of about 0.15% Mg in herbage DM is required by milking cows (Osbourne, 1980) and Mg deficiency in livestock is relatively common (Spedding and Diekmahns, 1972).

Leaching losses of Mg may be 2 to 30 kg Mg ha^{-1} yr^{-1} (Cooke, 1978) whilst a 10 t crop of perennial ryegrass may remove 7 to 40 kg Mg (calculated from data quoted by Spedding and Diekmahns, 1972). On heavy soils, soil reserves are often sufficient to replace lost Mg whereas light soils are often deficient in Mg (Cooke, 1975).

The concentration of Mg in sludges is about 0.4% in dry solids (Table 2)so a 5 t ha^{-1} application would supply about 20 kg Mg ha^{-1}.

The influence of sludge Mg on soil and plant Mg levels has not been extensively investigated. Coker(1966b) found applications of LDS increased herbage Mg from 0.135% to 0.156% in a two year experiment on ryegrass. King and Morris (1972) found large applications of LDS had no effect on herbage Mg concentrations but reduced soil extractable Mg. The Mg concentration in the sludges used was rather low (0.1% on dry solids). Soon et al. (1978) found both chemically treated sludges and NH_4NO_3 increased the concentration of Mg in bromegrass.

The limited information available suggests sludge Mg may be of some value on light soils, depending on the concentration present in the sludge.

2.3.10 Soil organic matter

Organic matter in soil forms organo - mineral complexes with clay particules resulting in the formation of stable soil aggregates. This improves water retention, drainage and aeration and assists root penetration. Soil organic matter contributes substantially to the soil CEC, especially on light soils (Allison, 1973).

The amount of organic matter in sludges depends upon the type of sludge. LPS and LAS contain 60 - 80% organic matter whereas LDS contains 30 - 60% organic matter (Table 2). A 5 t ha^{-1} application of LPS or LAS will therefore supply 3 - 4 t organic matter whilst the same amount of LDS will supply 1.5 - 3 t organic matter.

Large applications of sludges were reported to increase soil aggregate stability (Epstein 1975, Morel et al., 1978, Kladivko and Nelson, 1979), water holding capacity (Bunting, 1963, Epstein, 1975, Epstein et al., 1976, Gupta et al., 1977), CEC (Epstein et al., 1976) and bulk density (Hall and Coker, 1981). The effect of smaller applications repeated over many years depends on the speed at which the organic matter decomposes. Incubation experiments suggest a more rapid decomposition of the organic matter from LPS and LAS compared with that from LDS and solid sludges (p 16). Hall and Coker (1981) estimated about 80% of the organic matter applied in lime copperas or polyelectrolyte treated sludge had decayed by the end of 3 years.

Given the high organic matter content of most grassland soils these investigations suggest that the organic matter applied when sludges are used as N fertilizers is unlikely to be of agricultural importance.

2.3.11 Earthworm population

This brief review has been adopted from Edwards and Lofty (1972) except where stated otherwise.

Earthworm activity improves soil fertility by increasing aeration and soil aggregate formation, assisting root penetration and accelerating the decomposition of organic matter and mineralization of organic N. Earthworms were estimated to deposit between 18.7 and 40.3 t worm cast ha^{-1} yr^{-1} on the soil surface of pastures. Casting was found to be greater on heavy soils than on light soils.

Estimates of the population of earthworms in different pasture soils have ranged from 254 to 848 individuals m^{-2} or 51 to 287 g live weight m^{-2}. The species characteristic of pasture soils are Lumbricus terrestris, Allolobophora longa, Allolobophora caliginosa and Octolasium cyaneum although other species may also be present.

The application of inorganic N fertilizers was usually found to increase the earthworm population, probably due to the increase in organic matter input to the soil. However $(NH_4)_2SO_4$ applications were found to reduce the earthworm population, possibly by increasing soil acidity. Applications of organic manure to grassland at Rothamsted were found to increase the earthworm population 3 to 4 fold. Pain (1974) found frequent applications of cow slurry to reduce the proportion of L. terrestris but increase the proportion of A. longa and A. chlorotica in comparison with inorganic fertilizer treated grassland.

The effect of the application of sludge on the earthworm population of soil under grass has not been investigated. However the activity of Eisenia foetida in sludge drying beds (Mitchell et al., 1980) suggests that earthworms can feed on sludge solids. The same species was shown to tolerate a high concentration of PTE's in sludge (Hartenstein et al., 1980).

The effect on the earthworm population of heavy sludge applications to arable land was studied by Andersen (1979). The sludge was found to increase the number and biomass of L. terrestris and A. longa but to suppress other species. Cow slurry and inorganic N fertilizer applied to the same soil did not lead to a marked alteration in the relative species abundance. The selective effect of sludge PTE on the different species was implicated.

2.3.12 Conclusion

Sludge applications increase DM yield and the concentration of CP and NO_3^-- N in the grass but are likely to decrease the WSC concentration. The effect on the digestibility and concentration of Ca and Mg in the grass is likely to be slight. There is insufficient information available to determine whether any effect of the sludges on the DM yield and concentration of CP, WSC, digestible matter, NO_3^-- N, Cu and Mg in the grass produced can be solely attributed to the activity of the available sludge N. Applications of sludge are unlikely to elevate concentrations of PTE's in the grass in the short term unless sludge solids adhere to the grass leaves. The concentration of PTE's in the soil is likely to be raised.

The availability of sludge P is too variable to determine the effect of sludge application on the soil P reserve. The supply of sludge Ca usually exceeds the depleting action of the sludge N. In the absence of any other factors depleting the soil Ca reserve, the use of sludge as N fertilizers might be expected to increase soil pH. The supply of organic matter in the sludge is unlikely to be of direct agricultural importance although some benefit may be derived via the stimulating effect on earthworm numbers.

CHAPTER 3

FIELD TRIAL: MATERIAL AND METHODS

3.1 Introduction

Incubation experiments can give an insight into the transformations of sludge N in the soil but cannot faithfully duplicate the variability and interactions of environmental factors which occur in grassland soils. The best estimate of the availability of sludge N to grass is obtained by measuring the response of grass to application of sludge in the field. Glasshouse experiments suffer from some of the limitations which affect incubation experiments but do permit a manipulation of environmental factors which is difficult or impossible to achieve in the field.

Estimates of the availability of sludge N to grass in the field are obtained by comparing the response of the sward to applications of the sludge to the response to applications of an inorganic N fertilizer (p12). The trial sward must not be suffering a deficiency of any other nutrient which may be supplied by the sludge if the response is to be attributed solely to the activity of the sludge N. The response is usually measured in terms of the DM or N yield of the grass harvested. DM yield is easier to measure than N yield but estimates of the sludge availability may be erroneous if the efficiency with which sludge N is used to create DM differs from that of the inorganic N fertilizer (p 24).

The N yield of grass harvested from plots receiving an N source depends upon the total N supply (soil N + fertilizer or sludge N). The increase in N yield due to the application of an N source (termed the apparent N recovery) can be determined by subtracting the N yield of the untreated (control) plots from that of the plots receiving the N source. However investigations using ^{15}N labelled inorganic N have found that some of the additional N absorbed by the plants receiving fertilizer originated in the soil. A recent investigation on cereal crops found this additional soil N to represent on average 41% of the N yield response (Broadbent and Carlton, 1980). The source of this discrepancy has been attributed to either a stimulation of the mineralization of soil organic N, an enhancement of root growth leading to a greater exploitation of soil N or an exchange of labelled N with native N during soil N cycle transformations (Allison, 1965, Hauk, 1981). Although LDS N has recently been found to stimulate uptake of additional soil N (Thomas, 1981), it is not known whether the effect of the sludge differs from that of the inorganic N fertilizer when supplying the same amount of available N.

The use of ^{15}N in this field trial was not considered justifiable because of the high cost of obtaining and analysing for ^{15}N and the practical difficulties involved in the synthesis of ^{15}N labelled sludges. The estimation of the availability of the N in the sludges was therefore based upon the comparison of the N yield responses and it was assumed that the effect of the sludges and inorganic N fertilizer on the uptake of additional soil N was the same when the same amount of available N was supplied.

An estimate of the availability of sludge N can be obtained from the comparison of the response to one level of sludge and inorganic N fertilizer. However it is more common to apply several levels of sludge and inorganic N fertilizer and define a response line for each source of N. This method increases the confidence with which the response to the N sources is measured and enables variations in the rate of response at different levels of application to be identified. This approach has been adopted in the field trial.

Experimental methods were adopted on the advice of experienced agronomists or were improvised. Subsequently the techniques available for field investigations into the fertilizer value of sludges and for grassland experimentation in general have been reviewed (Coker, 1979, Hodgson et al., 1981). The techniques used in this trial broadly agree with those recommended in these publications.

3.2 Materials

3.2.1 Sludges

There are many combinations of treatment processes by which a sludge can be produced. Only a small number of sludges could be examined with the resources available. The choice was made on the following criteria:-

1) The sludges must represent types which are commonly applied to grassland.

2) The concentration of PTE's should be sufficiently low that they did not limit sludge applications in the short term.

3) The sludges should be accessible to the experimental sites and preferably be from STW's within the jurisdiction of the Severn Trent Water Authority.

The choice was assisted by some existing analyses provided by the water authority.

Liquid digested sludge

A liquid heated anaerobically digested sludge was obtained from the Monkmoor Sewage Treatment Works, Shrewsbury, Shropshire. A co-settled primary and humus sludge is digested at about 35°C with a retention time in the digester of between 17 and 21 days (as measured by the tracer method). The digested sludge is thickened in settling tanks for a period of one to several weeks depending on the agricultural demand for sludge.

Liquid activated sludge

A liquid surplus activated sludge was obtained from the Market Drayton Sewage Treatment Works, Shropshire. Untreated sewage is screened to remove solids larger than about 2 cm in size. The material removed is macerated then returned to the sewage flow. The sewage passes to an oxidation ditch where it is aerated and mixed by roller mounted brushes. The outflow from the ditch is regulated by an adjustable weir set in one wall. Both the rate of aeration and the removal of treated sewage is controlled manually according to the O_2 concentration in the ditch. The nominal retention time is 36 hours but the actual retention time varies with the density of the material concerned due to the action of the outflow regulating mechanism. The treated sewage is thickened in settling tanks for one to two days prior to disposal on agricultural land.

Solid sludge

An aluminium chlorohydrate pressed cake (PC) was obtained from the Pirehill Sewage Treatment Works, Stone, Staffordshire.

A co-settled primary and humus sludge is conditioned with aluminium chlorohydrate at a rate of about 2% dry solids. The conditioned sludge is dewatered in a press then stored in heaps (0–1 months) prior to disposal on agricultural land or tip.

Sludge chemical composition

The analyses of the LDS, LAS and PC are given in Table 7. The methods of sampling and analysis are given on p 47 and p 50.

The solids content, loss on ignition, pH and nutrient concentration of the three sludges were similar to the values reported in the literature (Table 2). The NH_4^+– N concentration in the LDS was lower than that found by other UK authors (Coker, 1979, Edgar et al., 1981) due to the post digestion thickening of this sludge. The percentage of the total NH_4^+– N estimated to be present as exchangeable NH_4^+– N held on the digested sludge solids was between the values reported by Coker (about 20%,

Table 7 The Chemical Composition of the Sewage Sludge used in this Investigation

Component	Units	LDS	CV (%)	LAS	CV (%)	PC
Solid	% fw	5.27	25.1	2.12	25.3	32.8
LOI	% ds	59.7	7.9	72.4	4.6	73.5
pH	-	7.45	7.9	7.41	26.9	6.37
Total N	kg t^{-1} fw	1.83	18.1	1.21	37.2	8.13
Total N	% ds	3.58	18.1	5.70	15.4	2.48
Organic N	% ds	2.53	12.3	5.33	16.1	2.48
NH_4^+ - N	kg t^{-1} fw	0.563	14.4	0.08	82.3	ND
NH_4^+ - N	% ds	1.02	39.0	0.38	79.5	ND
NH_4^+ - N	% Total N	31.4	19.9	6.6	80.8	ND
Exchangeable NH_4^+ - N	% Total NH_4^+ - N	14.4	25.3	ND	ND	ND
Total C	% ds	29.5		35.9		39.6
C:N (whole sludge)		8.3		6.3		16.3
C:N (solid fraction)		11.7		6.7		ND
P	% ds	1.47	15.9	1.48	6.1	0.66
K	% ds	0.18	37.8	0.33	40.5	0.06
Ca	% ds	3.52	25.3	3.29	29.3	2.35
Mg	% ds	0.36	26.2	0.25	32.6	0.16
Al	% ds	1.86	33.4	0.48	14.8	1.79
B	g t^{-1} ds	74.5	20.3	108.2	38.0	27.1
Cd	g t^{-1} ds	7.9	34.1	2.4	-	2.5
Cr	g t^{-1} ds	163	31.6	43	21.7	34
Cu	g t^{-1} ds	353	26.4	453	17.7	330
Pb	g t^{-1} ds	425	15.7	259	16.0	245
Ni	g t^{-1} ds	45.4	24.3	22.5	14.8	16.5
Zn	g t^{-1} ds	1108	31.7	542	19.8	615
Zn equivalent	g t^{-1} ds	2177	18.0	1630	15.5	1430
n =		11		14		2

CV = Coefficient of variation

n = number of samples
ND = not determined

LOI = Loss on ignition   ds = dry solids pers. comm.) and those of Beauchamp et al. (1978). The concentration of PTE's, with the possible exception of Al, were lower than those commonly reported in the literature (Table 2). The relationship between the concentrations of the elements in the three sludges was similar to that described on p 9.

The concentrations of most of the elements were normally distributed ($p < 0.05$) as determined by the method given in 3.3.12. Exceptions were the distributions of the total N and NH_4^+- N (expressed as dry solids), K, Mg and Zn concentrations of the LDS and the pH of the LAS which were positively skewed.

The normality of the distribution of most of the PTE's in the LDS contrasts with the positive skewness of distribution reported by Sommers (1977). The variations in the concentrations of elements were lower than those reported by Sommers (1977) but similar to those found by Kelling et al. (1977). The normality of distribution and low variability of the PTE concentrations may reflect the domestic origin of the sludge although it is also possible that the number of samples analysed were not sufficient to fully describe the distribution. The skewness in the distribution of LAS pH could be traced to one sample (pH 12.4) obtained whilst the main sewers were being flushed.

Although most of the NH_4^+- N in the LDS is in the liquid fraction, it is conventional to express the NH_4^+- N content on dry solids. This tends to increase the apparent variability of the NH_4^+- N content (Sommers, 1977, Table 3). The agricultural importance of the true variability in the NH_4^+- N and total N content of the liquid sludges is discussed in Chapter 9.

3.2.2 Inorganic fertilizers and water

The mineral fertilizers used were those commercially produced for use in agriculture and were obtained from Garners of Newcastle. The inorganic fertilizers are described in Table 8.

Table 8 Inorganic Fertilizers used in this Investigation

Nutrient	Fertilizer	Nutrient Content % Dry Weight	Form
N	Ammonium nitrate	34.5 % N	prilled
P	Superphosphate	18 - 22 % P_2O_5	powder
K	Potassium sulphate	53.8 % K_2O	granules
Mg	Magnesium sulphate	20.0 % Mg	granules
Ca	Hydrated lime	70 % NV*	powder

* NV = Neutralising Value: effect on soil pH compared to CaO

The water used was obtained from the domestic supply.

3.2.3 Sites

A definitive investigation into the effects of soil type on the performance of sewage sludge as nitrogenous fertilizer would require field trials on many sites representing a range of clay and organic matter contents, parent material and drainage types. This would require an investment of resources beyond the scope of this project. Since the soil type was not expected to have a dramatic effect on the performance of the sludges (p 18) the investigation was restricted to two sites. The criteria upon which the choice of location was made were:-

1) The soils should have considerably different clay contents.

2) Both soils should be currently sown to pasture.

3) The site should be near to Keele and accessible by tanker.

4) The farmers should be co-operative.

A description of the sites chosen is given in Table 9. A profile of the soil at both sites is shown in Plates 1 and 2. Topographic details are shown in Fig 3 Meteorological data for 1979 and 1980 are

Table 9 Description of Experimental Sites used in this Investigation

	Site A	Site B
Location	Swynnerton Heath Farm	Reaseheath College of Agriculture
OS reference	SJ 846376	SJ 653547
Altitude	171 m	44 m
Soil type	Well drained sandy loam over gravel	Poorly drained stoneless clay
Particle size analysis to 7.5 cm depth	sand 74.5% silt 13.3% clay 12.3%	sand 26.7% silt 30.6% clay 42.7%
Depth of water table	30 m	0 - 0.5m
Bulk density	1.18 ± 0.22 g cm^{-3} *	0.95 ± 0.11 g cm^{-3} *
Total pore space	57.3%	62.5%
Moisture content at field capacity (50 cm water tension)	34.6%	52.1%
Analysis to 7.5 cm depth:- **		
pH	6.17	5.35
Organic matter	about 5%	about 11%
Cation exchange capacity	10.9 meq 100 g^{-1}	25.1 meq 100 g^{-1}
Total nitrogen	0.17%	0.44%
Extractable P	42.6 mg ml^{-1}	50.2 mg ml^{-1}
" K	53.5 mg ml^{-1}	88.5 mg ml^{-1}
" Mg	approx 25 ppm	> 200 ppm
Previous history	7 years under grass	7 years under grass

* 95% confidence limits

** Analytical methods described in 3.3.9

Plate 1 The soil profile at Site A

Plate 2 The soil profile at Site B

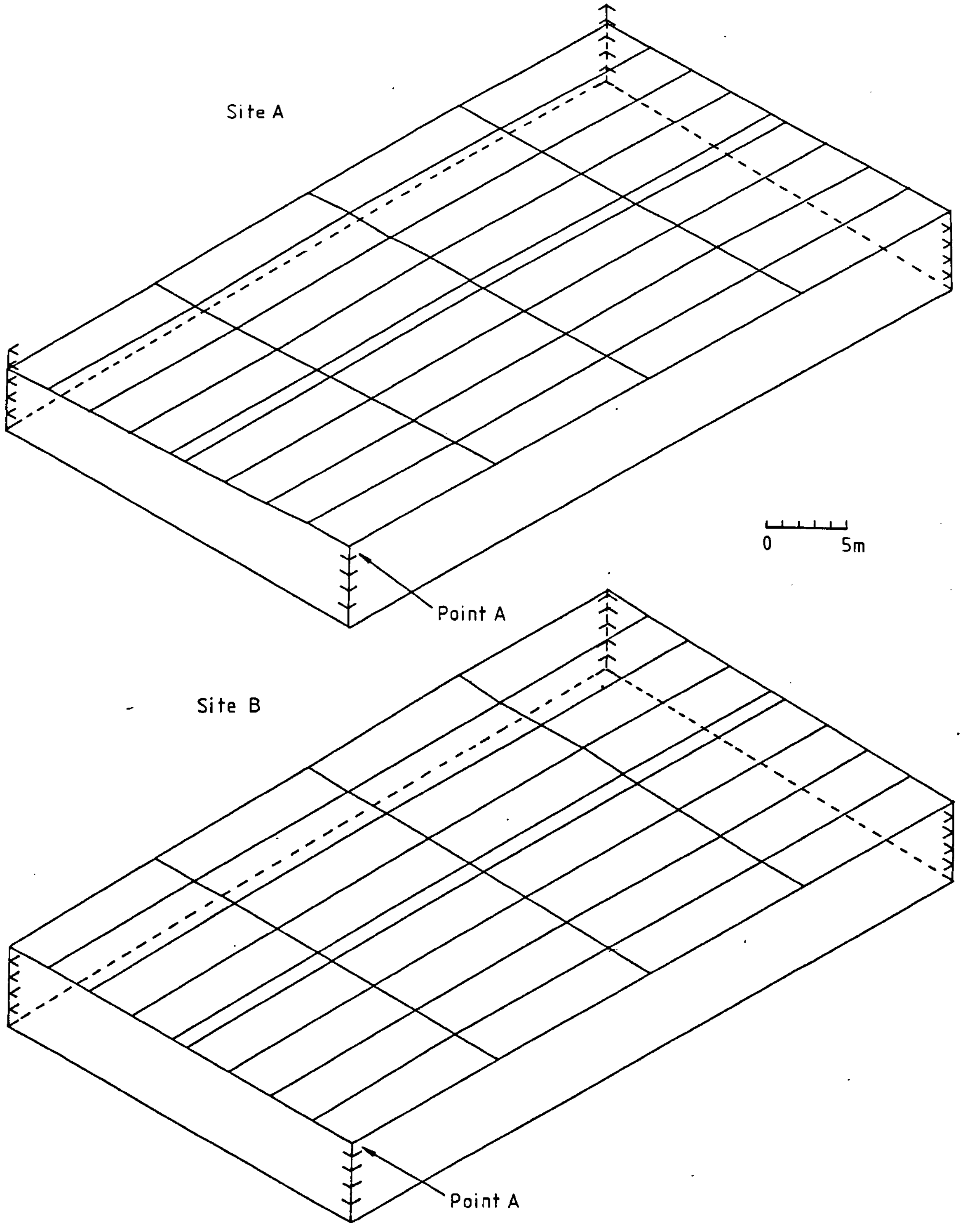


Fig 3 Topographic description of the experimental sites. Point A enables this figure to be orientated with Figure 7 and Plate 3.

presented in Fig 4 to 6 The 10 cm soil temperature was measured hourly at each site using Grant temperature recorders. The soil moisture was measured periodically at each site using a Crump saturometer. It was found necessary to calibrate the saturometer against the actual soil moisture of soil samples from each site (Appendix 2). The rainfall data was obtained from the Keele meteorological station.

3.2.4 Grass species

Perennial ryegrass (Lolium perenne L.) is the most widely sown grass species in this country. The cultivar S23, although now superseded by more productive varieties, is still recognised as a standard in varietal testing (eg, NIAB yearly publication of recommended varieties). This variety was therefore sown at both sites in the spring of 1978 using seed obtained from the Welsh Plant Breeding Station.

3.3 Methods

3.3.1 Establishment of sward

In March of 1978 the existing sward on both sites was killed with paraquat. Phosphate fertilizer (88 kg P_2O_5 ha^{-1}) and potassium fertilizer (88 kg K_2O ha^{-1}) was applied and the soil surface rotovated to a depth of about 20 cm. Lolium perenne cv S23 was sown by hand at a rate of 44 kg ha^{-1} and rolled in by a hand pulled roller. Baited bran was applied to prevent leatherjacket attack. A good establishment was achieved and the grass was cut and removed in mid June.

During establishment and throughout the duration of the field trial, broadleaved weeds and clover were suppressed with spot applications of MECOPROP*. This was supplemented with an application of NORTRON* in the autumn of 1978. Although some invasion of weed grasses did occur, especially where high nitrogen applications led to the development of an

* Obtainable from Fisons Agrochemicals Division

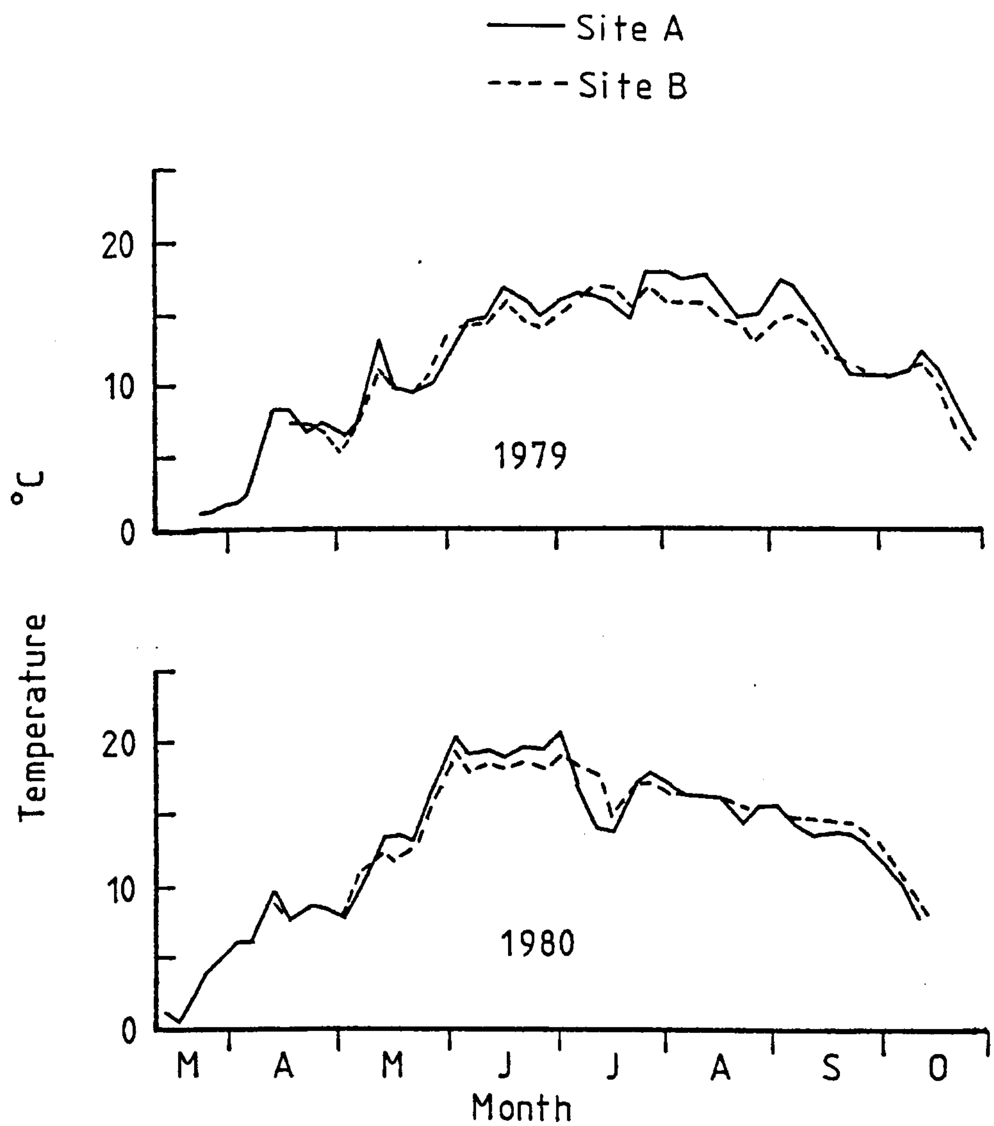


Fig 4 The mean five day 10cm soil temperature in 1979 and 1980.

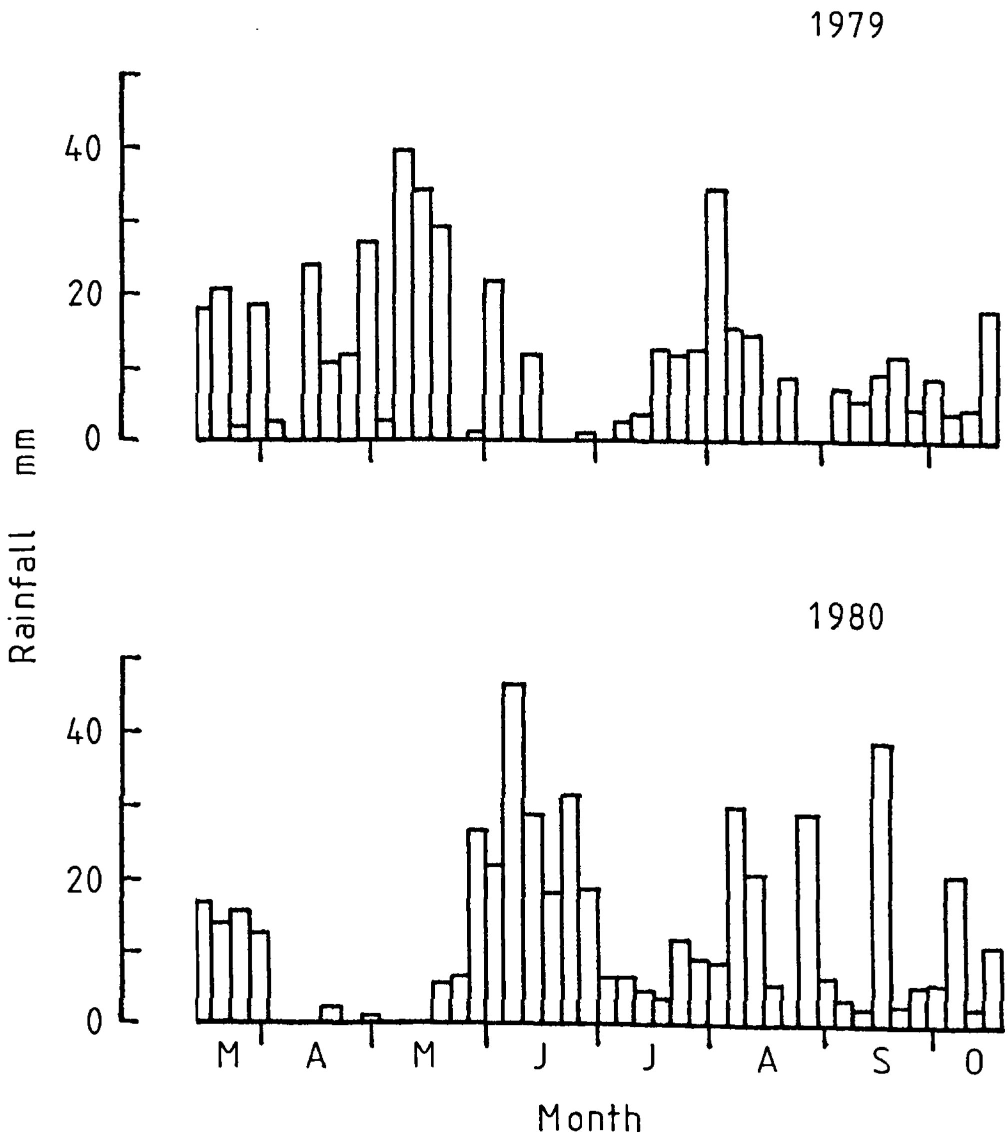


Fig 5 The distribution of rainfall over the growing season in 1979 and 1980.

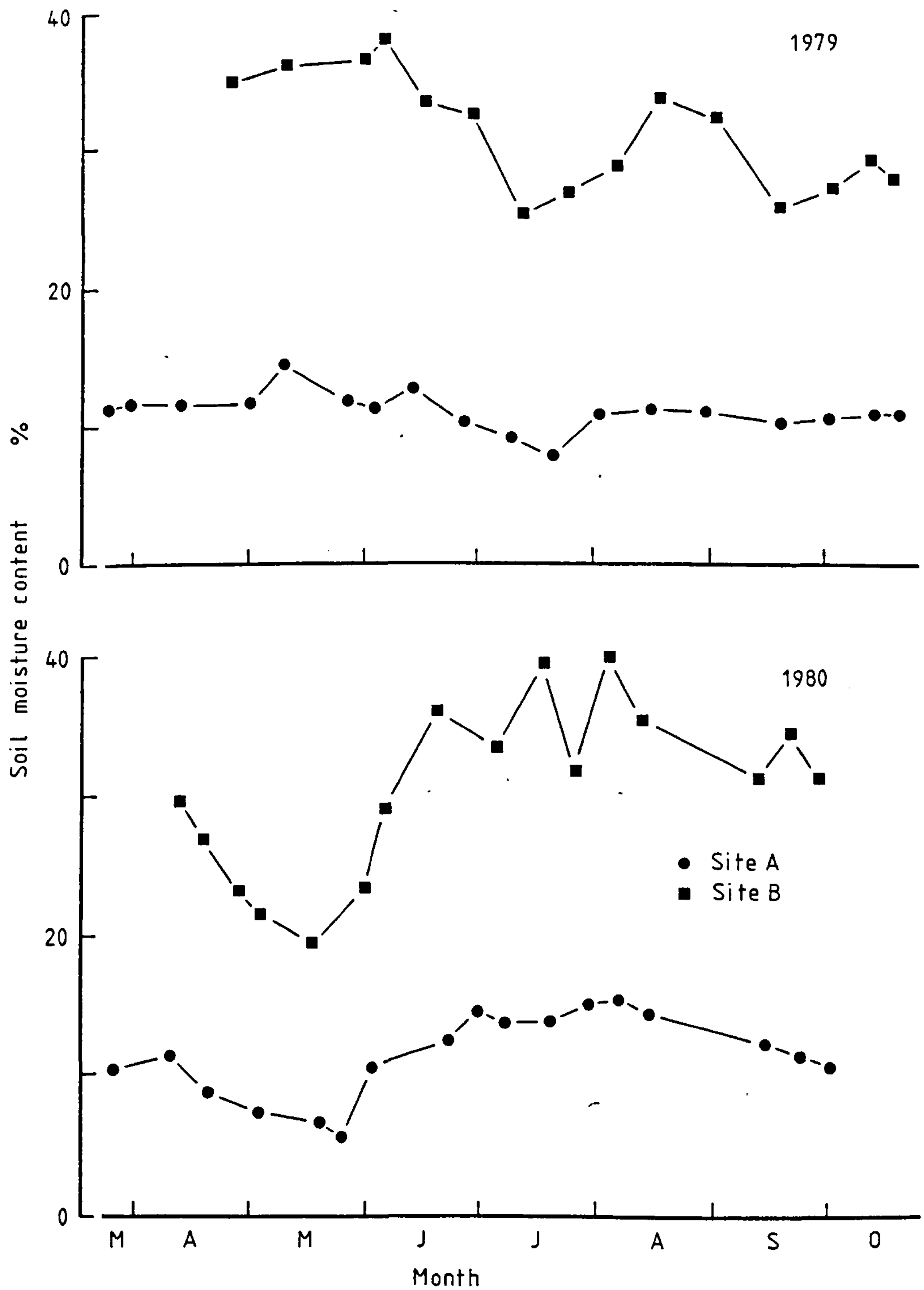


Fig 6 The soil moisture content at the experimental sites in 1979 and 1980.

open sward, the Lolium perenne remained the dominant species throughout the duration of the field trial.

3.3.2 Treatments

The field trial had three components (Table 10):

Component 1 established the response lines for inorganic N, LDS and LAS. Treatments were repeated four times a year.

Component 2 examined the possibility that part of the response to the sludges was due to a H_2O and/or N x H_2O interaction. These treatments were applied at the same time as those in component 1.

Component 3 assessed the primary and residual response to the use of a single large application of LDS, LAS or PC, timed to take advantage of the reproductive growth period in the spring.

The PC was omitted from component 1 since it was not considered suitable for application to non-arable land. An autumn application was included in component 3 to determine if this sludge might be of value if permitted to break down over winter. The course of the physical breakdown of the PC solids was monitored in 1980 (Appendix 3).

The levels of inorganic N used in component 1 were chosen to determine the full range of the DM response to N (see p 23). The sludge N was applied as close as possible to the same levels on the null hypothesis that the sludge N was as available as the inorganic N. Practical difficulties meant that the target application rates of sludge were not always achieved. The rate of application of N in component 2 was chosen to ensure a detectable response whilst remaining within that part of the response line which was expected to be approximately linear. Since a N x H_2O interaction was thought most likely to occur through LDS applications, the H_2O was applied at a rate equivalent to that in the LDS treatment supplying the same level of N. A high rate of application of N in component 3 was chosen to ensure

Table 10 Treatments applied in the Field Trial

Component	Treatment Symbol	Nitrogen Source	Application Rate	Pattern of Application
	C	control	-	-
1	AN1	NH_4NO_3	100 kg N ha^{-1} yr^{-1}	4 equally split
	AN2	"	200 "	
	AN3	"	300 "	
	AN4	"	400 "	
	LDS1	liquid	100 "	
	LDS2	digested	200 "	
	LDS3	sludge	300 "	
	LAS1	liquid	100 "	
	LAS2	activated	200 "	
	LAS3	sludge	300 "	
2	W	water equivalent to LDS2	-	
	W + AN2	as above + AN2	200 kg N ha^{-1} yr^{-1}	
3	LDS(s)	liquid digested sludge	150 kg N ha^{-1} yr^{-1}	spring only
	LAS(s)	liquid activated sludge	150 "	spring only
	PC	pressed cake	150* "	autumn only

* 400 kg N ha^{-1} yr^{-1} in 1979

that any substantial residual effect would be detectable. The upper limit to the rate of application was determined by the wish to avoid the loss of N by leaching. The application rate of PC was increased in 1979 since the lower rate had little effect in the previous season.

The analytical program for grass samples is described in Table 11.

On the termination of the field trial, soil samples were taken from treatments AN3, LDS3, LAS3, PC and C for the determination of loss on ignition (organic matter content), total N, extractable P and soil pH. Quadrats (0.25 m^2) were placed within plots receiving these treatments and earthworms were extracted with formalin.

Table 11 The Analytical Program for Grass Samples from the Field Trial

Component	Dry Matter content	Total N	NO_3^--N	MADF**	WSC	Ca, Mg	PTE's***
1	all cuts	all cuts	level 3	all cuts	all cuts	level 3	level 3
2	all cuts	all cuts					
3	all cuts	all cuts	1st cut*	1st cut	1st cut	1st cut	1st cut

* 1st cut in both 1979 and 1980

** Facilities for the determination of digestibility were not available. The modified acid detergent fibre (MADF) is related to the D value by the equation: D value = 99.4 - 1.17 MADF (Martin, pers. comm.)

*** PTE's = Cd, Cr, Cu, Ni, Pb and Zn

3.3.3 Experimental design

The variation in the topography of both sites made it advisable to select a randomized block design. The positioning of the blocks may be seen by comparing Fig 3 and 7. At both sites there were four blocks, each containing sixteen 1.5m by 10m plots. The sixteen treatments were randomized within each block, the same layout being used at both sites (Fig 7, Plate 3). Plots were identified in the field by lines stretched between markers placed around the edge of the experimental area.

Due to a lack of space and manpower, treatments had to be repeatedly applied to the same plots. This inevitably led to the confounding of the primary and residual effects of applications.

3.3.4. Cropping system

The first application of treatments in both years was made in late March or whenever soil conditions permitted. Subsequent applications (where relevant) were made in early June, mid July and late August. In 1979 the target date for applications was one or two days after the harvesting. Practical difficulties associated with the supply of liquid sludges delayed the applications on three occasions. In 1980 the target

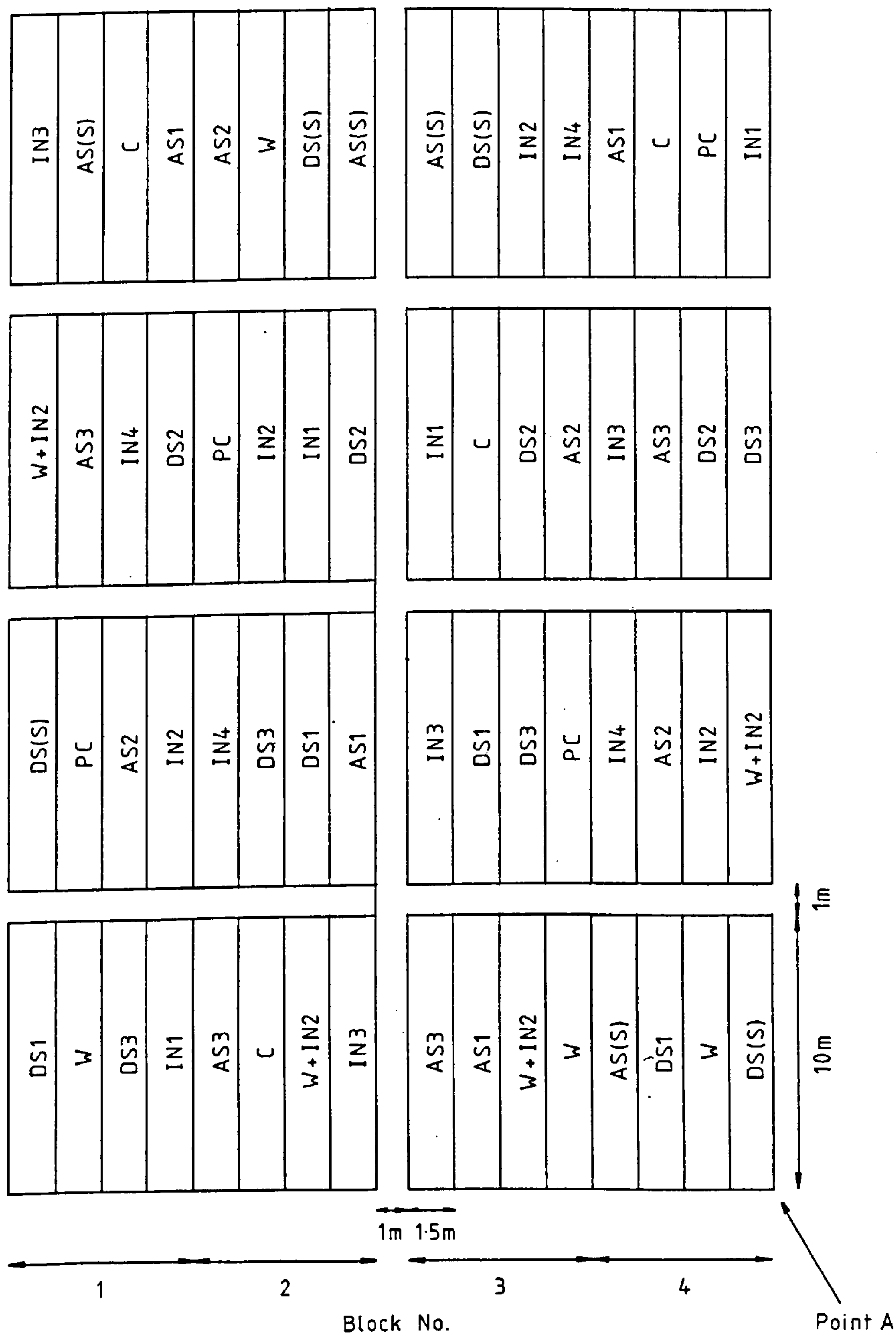


Fig 7 The layout of the field trial. Point A is given to enable this figure to be orientated with Fig 3 and Plate 3.

Plate 3 Plot layout

date was moved to seven days after the harvest and all applications were made on time. The actual application dates are given in Table 12. It is unlikely that there was a serious loss of yield due to the delays in application.

A four cuts per year harvesting system was adopted. The number of harvests taken in the year was largely determined by the availability of manpower and machinery. The dates of harvesting are given in Table 12.

Table 12 Application and Harvesting Dates in the Field Trial

	Year	Application or Harvest Number			
		1	2	3	4
Application dates	1979	20.3/3.5*	11.6/11.6	20.7/20.7	5.9/6.9
	1980	3.4/17.4	20.6/19.6	24.7/24.7	21.8/22.8
Harvest dates	1979	6.6/7.6	18.7/19.7	29.8/30.8	23.10/24.10
	1980	12.6/13.6	16.7/17.7	18.8/19.8	3.10/4.10
PC treatment applications	1978	14.11/14.11			
	1979	13.12/14.12			

* Site A/Site B

3.3.5 Maintenance of soil nutrient status

Phosphate

The P requirement was calculated using MAFF recommendations (1975) from the estimated DM production and from soil analyses conducted in winter 1978/1979. Sludge P was assumed to be 100% effective as a maintenance dressing, so it was sufficient to supply the calculated P requirement without inorganic fertilizer. The extractable soil P in soils receiving sludge was checked in the winter 1979/1980. P fertilizer was applied plot by plot in late winter.

Potassium

In 1979 the K requirement was calculated using MAFF recommendations (1975) from the estimated DM production and from soil analyses conducted in winter 1978/1979. The K fertilizer was applied in 4 equally split applications after each cut. In 1980 an application of 90 kg K_2O ha^{-1} was made to all plots after the first cut and 60 kg K_2O ha^{-1} after subsequent cuts. The simplified system was adopted in 1980 to save time at particularly busy times of the year.

Lime

The lime requirement was determined by soil analysis (MAFF, 1973). The target pH was 6.0. Lime was applied in a single amount in late winter.

Magnesium

No Mg fertilizer was applied on Site B since the soil contained sufficient extractable Mg (Table 9). Mg fertilizer was applied on Site A at a rate of 90 kg Mg ha^{-1} in late winter.

3.3.6 Methods of application

Liquid sludges

Two days before the target application date the liquid sludges were transported from the treatment works to the experimental sites by tanker (Plate 4). The loading and unloading procedure was the same at both works and sites.

The tanker was washed out with half a load of the sludge to be transported. This prevented contamination from any sludge remaining in the bottom of the tank from previous loads. A two-third load was taken from the bottom of the settling tank. This was generally sufficient to supply both sites.

Plate 4 Delivery of sludge to an experimental site

At each site the sludge was unloaded into 220 l plastic drums and covered until used. A sample of sludge (approximately 150 cm^3) was taken from each barrel (6-12 in number) and the samples bulked within sites. Samples were returned to the laboratory and stored at 1°C until required for analysis. The similarity in the solid content of the sludges from the two sites suggests settling during transport was not a problem.

The total N content of each sludge at each site was determined according to the method given in 3.3.9 . From this information the volume of sludge required to supply the designated quantity of N was determined. This figure was rounded to the nearest litre (up to July 1979) or the nearest 5 litres (from August 1979 and 1980).

Up to July 1979 the liquid sludges were applied by hand from 10 l plastic bottles (Plate 5). This method was very labour intensive and at low application rates the distribution of sludge was irregular. In August 1979 and for all applications in 1980 sludge was spread direct from the storage drums via a Honda G150 pump and a 2.5 cm dia PVC pipe with ball valve (see Fig 8). The volume of sludge to be applied was marked off on a graduated dipstick. Between applications material remaining in the pump and pipes was thoroughly flushed out with the next material to be applied.

This mechanical application system reduced the labour requirement and improved the spread of the sludge but target rates had to be rounded up or down to the nearest five litres in order to maintain accuracy of application.

Pressed cake

PC was taken from a freshly produced batch (1 week old) and transported to the sites on a flat-bed trailer. Practical considerations made it desirable to collect and apply the PC on the same day. Consequently the application rate was estimated from previous analyses for moisture and N content.

Plate 5   Sludge application

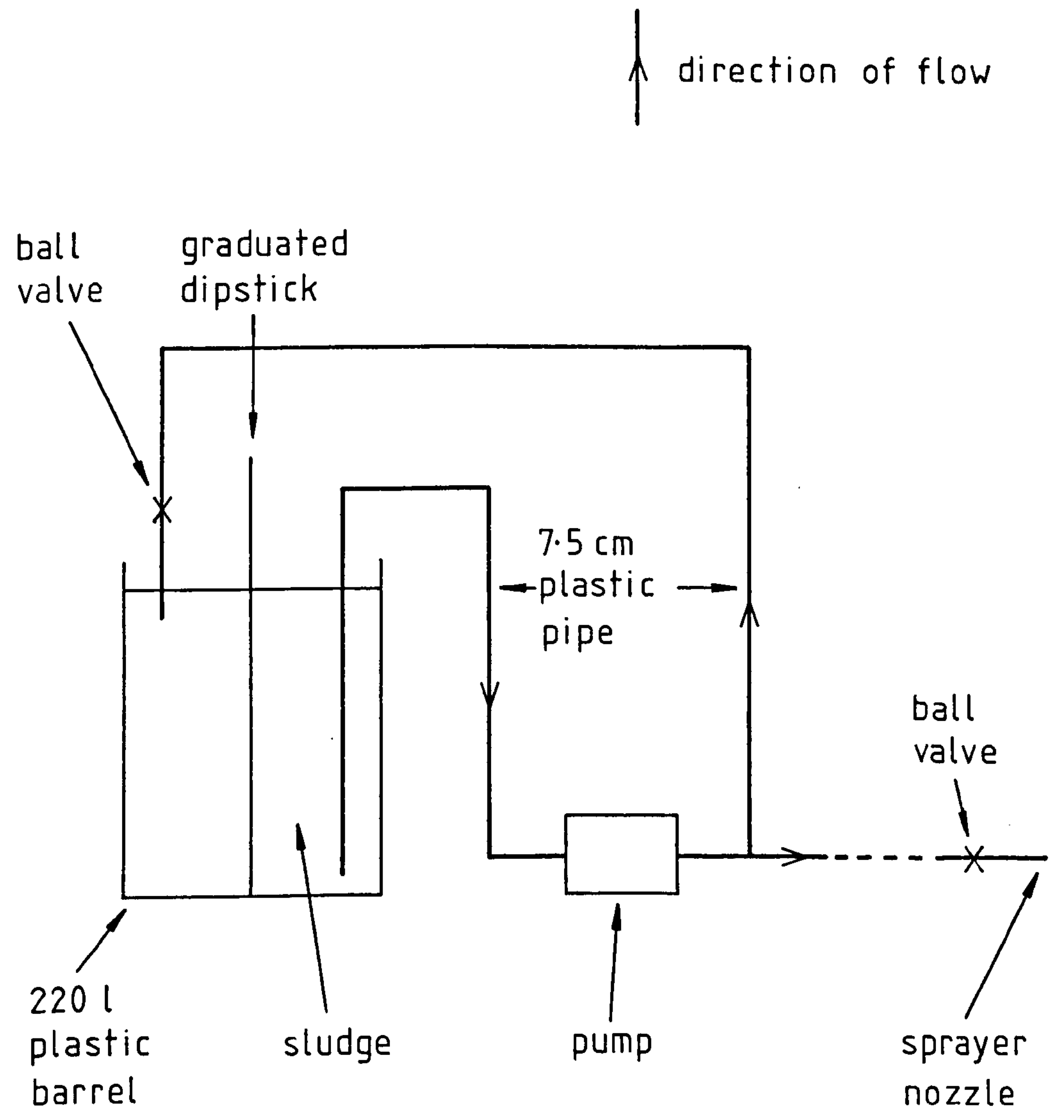


Fig 8 The pump-operated sludge spreading system

The PC was chopped with a spade into approximately 2.5 cm cubes (Fig 9). In 1978 the chopped cake was heaped and 25 cubes removed by hand to obtain a bulked sample for analysis. In 1979 the larger amount of PC applied made this sampling method impractical and so the sample was obtained by removing 1 cube per 5 kg applied (64 cubes in total) and bulking. In both years a sub-sample (about 150 g) was removed from the bulked sample by quartering and then dried in the laboratory to determine the moisture content (see p 51 for method).

The chopped PC required for each plot was weighed in 5 kg amounts using a spring balance (25 g divisions) then spread by hand.

Inorganic fertilizers and H_2O

Inorganic fertilizers which required plot by plot application (eg, N, lime) were applied by hand. Those which required general broadcasting (eg, P, Mg) were applied in a hand pulled cyclone seeder.

H_2O was applied by the system described for liquid sludges (p 49).

3.3.7 Method of harvesting grass

The grass was cut with an Allen autoscythe with a 0.91 m width reciprocating blade (Plate 6). The sample cut was taken down the centre of each plot, 0.3 m from each end. This gave a sample area of 8.55 m^2.

The cut grass was raked into piles and collected in plastic washing baskets (Plate 7). These were weighed using a spring balance (25 g divisions, 5 kg maximum weight) (Plate 8). All the grass from one plot was mixed together on a polythene sheet and three grab samples taken from within the pile. These were bulked to give a sub-sample of 200-300 g fresh weight per plot. The sub-sample was placed in a polythene bag together with an identifying number and sealed. The sub-samples were stored in the shade until harvesting was complete when they were returned to the laboratory.

The sub-samples were stored at -22^oC prior to further sub-sampling and analysis.

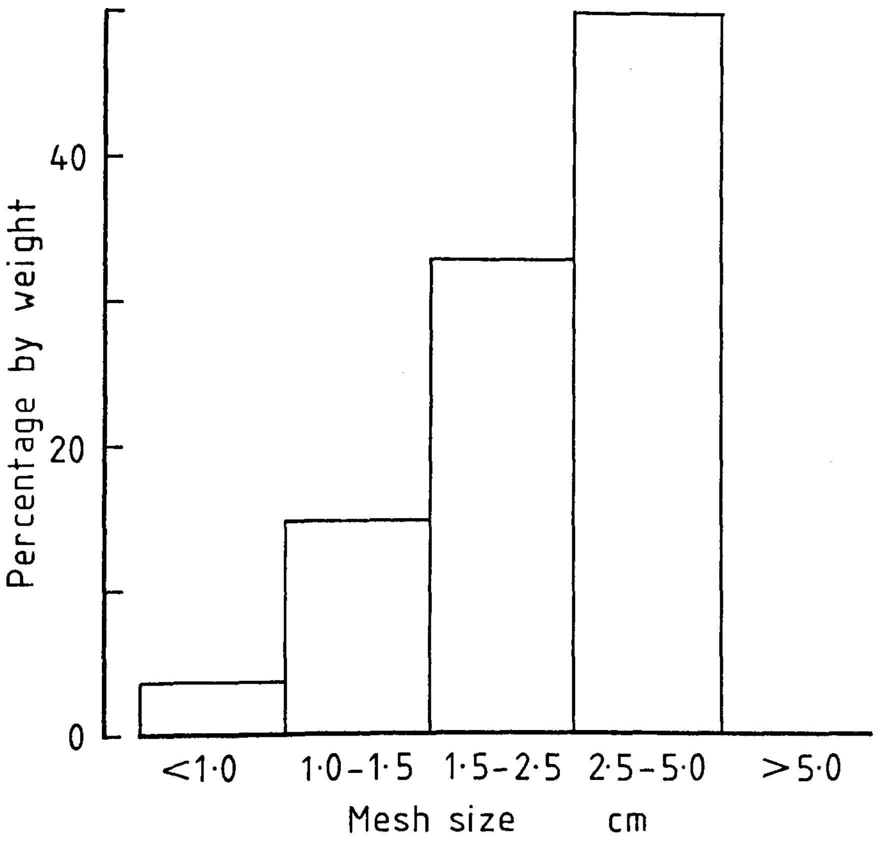


Fig 9 The size distribution of PC solids applied in 1979.

Plate 6   Grass harvesting

Plate 7   Raking the grass

Plate 8   Weighing the grass

3.3.8 Method of soil sampling

In March 1978 the soils were sampled with a 7.5 cm dia corer to a depth of 15.0 cm. Samples were taken at 3 m spacings along the three short paths. The 24 samples were bulked within sites.

Soil samples from December 1978 until October 1980 were taken with a 2.5 cm dia pot auger with a sampling depth of about 8 cm. A minimum of 25 samples were taken in a zig zag pattern up each plot. The samples were bulked within plots and returned to the laboratory in sealed, numbered polythene bags. Samples were kept at -22°C until dried.

3.3.9 Sludge analysis

Solid content

A weighed sub-sample of wet sludge (about 100 cm^3 liquid sludge or 150 g PC) was dried overnight at 100°C in a forced draught oven then reweighed. This was replicated five times for each sludge/site. The dried sludge from both sites was bulked then ground to pass a 2 mm sieve. The ground sample was retained for further analysis.

Loss on ignition

Dried, ground sludge (about 1 g, accurately weighed) was heated overnight at 500°C in a muffle furnace. The ashed sludge was cooled in a dessicator then reweighed to determine the loss on ignition.

Total carbon

The total C concentration in the sludges was determined on dried, ground sludge on a C.H.N. analyser in the Chemistry Department at Keele University. To reduce the cost, the samples of liquid sludges were bulked within years. The total C concentration in the PC was determined on a single bulked (1978 + 1979) sample.

Inorganic nitrogen

Preliminary analyses found the concentration of NO_3^-- N in both liquid sludges to be insignificant so this analysis was discontinued. The analysis of NH_4^+ - N was modified in 1980 to include an extractant to remove exchangeable NH_4^+- N.

1979: A sub-sample of sludge (about 300 cm^3) was centrifuged at about 3000 rpm for five minutes. This was found to be sufficient to bring out 96% of the LDS solids and 97% of LAS solids. The solid fraction was retained for the determination of organic N. A sample of the liquid fraction (10 cm^3) was diluted to 100 cm^3. A sample of the diluted liquid fraction (x cm^3) was analysed for NH_4^+- N according to the method given for soil extracts in MAFF (1973).

1980: A sub-sample of sludge (300 cm^3) was mixed with 20% $^w/v$ KCl solution (300 cm^3) and shaken for 30 minutes. A sub-sample of the mixture (about 300 cm^3) was centrifuged at about 3000 rpm for five minutes. The solid fraction was retained for the determination of organic N. A sample of the liquid fraction (20 cm^3) was diluted to 100 cm^3. Analysis of NH_4^+ - N proceeded as in 1979.

Towards the end of the trial it was decided that an accurate determination of the true NH_4^+- N content of a sludge was necessary if the true availability of the mineral and organic sludge N was to be assessed. Failure to account for exchangeable NH_4^+- N may have led to an inflated estimate of sludge organic N net mineralization. This is not very important for LAS since the NH_4^+- N content is low and the activity of the sludge organic matter high. To estimate the exchangeable NH_4^+- N in the LDS used in this trial, eight samples of LDS representing a range of solids contents were extracted with 20% $^w/v$ KCl and with distilled H_2O and the NH_4^+- N content determined in each extract. The difference between the NH_4^+- N concentration in the two extracts was taken as an estimate of the exchangeable NH_4^+- N. Details of the method used and the relationship between exchangeable NH_4^+- N and LDS solids content which was obtained are given in Appendix 5.

Organic nitrogen

1979 and 1980: The solid fraction of the sludge separated out during the determination of NH_4^+- N was washed three times with about 40 cm^3 distilled H_2O. The washed solid was then dried to constant weight at 100°C and ground to pass a 2 mm sieve in a hammer mill. The N content of this solid fraction (assumed to be organic N) was determined by the micro-digestion procedure given for plant material in MAFF (1973).

Phosphate

Dried, ground sludge was wet digested and analysed for P spectrophotometrically by the methods described for plant material in MAFF (1973).

Calcium, magnesium and potentially toxic elements

Dried, ground sludge was analysed for Ca, Mg and PTE's by the Malvern Regional Laboratories of the Severn Trent Water Authority.

pH

The pH of liquid sludge was determined by dipping the electrode of an EIL Model 7030 pH meter into a sub-sample of the sludge (about 25 ml). The pH of the PC was determined by adding sufficient water to a sample of sludge (about 40 g) to make a slurry. The pH was measured as for the liquid sludges.

3.3.10 Grass analysis

Sub-sampling and dry matter content

Samples straight from the freezer were chopped into 3 to 4 cm lengths using a vice-mounted hedge trimmer. The chopped sample was mixed thoroughly and quartered to obtain two sub-samples weighing 100 to 150 g.

One sub-sample was dried in a forced draught oven at 80°C until suitable for grinding. The sub-sample was ground to pass a 2 mm sieve in a Cristy Norris hammer mill then stored in sealed polythene bags prior to chemical analysis. A weighed sub-sample of this material (1 to 2 g) was dried overnight at 100°C then reweighed to determine the residual moisture content. Corrections were applied in subsequent analyses.

The other sub-sample was weighed, dried overnight at 100°C in a forced draught oven and then reweighed to determine the DM content.

Total nitrogen

A sample of dried, ground grass (about 0.1 g, accurately weighed), one selenium catalyst tablet (0.05 g Se + 2.5 g K_2SO_4) and 98% w/w H_2SO_4 (6 cm^3) were placed in a boiling tube and heated in a heating block until the digest had clarified + 15 minutes. After cooling, the digest was diluted to 250 cm^3. The diluted digest was stored at room temperature prior to analysis for NH_4^+- N on an auto-analyser at the Strongford Laboratory of the Severn Trent Water Authority.

This digestion procedure converts some but not all the NO_3^-- N to NH_4^+- N. This may have resulted in a small under estimation of the total N where the concentration of NO_3^-- N was high (see p 94). The method was found to give results comparable to those obtained using the micro-digestion method recommended by MAFF (1973).

Nitrate nitrogen

The NO_3^-- N was extracted with water from dried, ground grass as described in MAFF (1973). The extracts were analysed for NO_3^- on the auto-analyser at the Nottingham Regional Laboratory of the Severn Trent Water Authority. The extracts were stored at 1°C until analysed. The delay between extraction and analysis was 1 to 2 days.

Water soluble carbohydrate

The WSC was determined spectrophotometrically on a water extract by the method given in MAFF (1973).

Modified acid detergent fibre

The MADF was determined gravimetrically following mixed acid-detergent digestion according to the method given in MAFF (1973).

Calcium, magnesium and potentially toxic elements

The Ca, Mg and PTE's were determined on dried, ground grass samples by the Malvern Regional Laboratory of the Severn Trent Water Authority.

3.3.11 Soil analysis

Sample preparation

Soil samples were dried at 30°C in a forced draught oven until judged dry. The samples were gently broken up with a pestle and mortar and sieved to pass a 2 mm sieve. Prepared samples were stored in sealed polythene bags prior to chemical analysis.

Particle size distribution

The particle size distribution of the soil at Site A was determined by the method described in Allen et al. (1974). The particle size distribution of the soil at Site B was taken from the soil survey sheet SJ 65 (Crewe West). The Soil Survey testing site is adjacent to the experimental area.

Organic matter

The soil organic matter was estimated by the loss on ignition method described in Allen et al. (1974).

Potentially toxic elements

The concentrations of PTE's in the soils were determined by the Malvern Laboratory of the Severn Trent Water Authority.

pH and lime requirement

The soil pH was determined on a 1:2.5 soil:water mixture as described in MAFF (1973). The lime requirement of soil samples taken in the winter 1978/1979 was determined according to MAFF (1973). The correlation between the lime requirement and the pH was determined for both sites and the relationships modified to give a target pH of 6.0 instead of 7.0:-

Site A

$$\text{Lime requirement} = -3.02 \text{ pH} + 18.12$$
$$r = -0.76^{***}$$
$$n = 64$$

Site B

$$\text{Lime requirement} = -3.96 \text{ pH} + 23.76$$
$$r = -0.59^{***}$$
$$n = 64$$

These relationships were used to determine the lime requirement from pH measurements in subsequent years.

Earthworm population

A quadrat (0.25 m^2) was placed at random on the long axis of each plot to be examined, leaving a 1 m guard strip at each end. The earthworms were extracted using 0.5% formalin solution according to the method given by Raw (1959)

Although this method does not extract all species with the same efficiency (Lofty and Edwards, 1972) it was considered adequate to obtain results for comparative examination.

Extracted earthworms were killed in ethanol (70% $^v/v$) then returned to the laboratory. A preliminary examination of the samples found representatives of L. terrestris and Allolobophora spp. No E. foetida of O. cyaneum were found at either site although small O. cyaneum may have been mistakenly identified as Allolobophora spp. The earthworms in each sample were therefore separated into three easily identifiable fractions: L. terrestris, A. longa and A. caliginosa group (A. caliginosa, A. rosea, A. chlorotica). This crude separation was considered the best compromise between the desire to distinguish between the effects of the sludges on different species and the length of time required to seperate the smaller Allolobophora species.

The number of earthworms in each fraction was noted then the carcasses were dried at 100°C overnight and weighed.

Total nitrogen, extractable phosphate, extractable potassium, extractable magnesium and cation exchange capacity.

The total (Kjeldahl) N, $NaHCO_3$ extractable P, the NH_4NO_3 extractable K and Mg and the CEC were determined by the methods given in MAFF (1973).

3.3.12 Statistical analysis

The results of the chemical analysis of the sludges were examined for skewness and kurtosis by the method given in Snedecor and Cochran (1967).

All results from the field trial were analysed by a two - way analysis of variance (treatments x blocks) within each site or site/cut. Where relevant the coefficients of variation (standard error divided by the mean) were determined as a measure of the background variation of the results.

The significance of the differences between the N source effects within the Component 1 treatments (Table 10) were determined by a two - way analysis of variance followed by Tukey's W procedure (Tukey, 1949). The nature of the response of N yield, DM yield, CP, MADF and WSC to the levels of application of a single N source was investigated by a response analysis which extracted the linear (LIN), quadratic (QUAD), cubic and residual (RESID) components. The significance of the components was determined by comparing the variance associated with each with the error mean square obtained from the two - way analysis of variance of the complete set of results for that variable.

The significance of the difference between the Component 2 and 3 treatment effects (Table 9) on N yield, DM yield, CP, MADF and WSC and between all treatment effects on the other factors examined were determined by Tukey's W procedure. The error mean square was obtained from the two - way analysis of variance of the complete set of results.

The statistical methods applied to each set of results are given in each 'results' sub - section. Other statistical methods than those described here have been used occasionally and these are introduced when encountered.

3.3.13 Presentation of results

The results of the applications of treatments made during the seeding year (1978) are not presented here as the response of the sward may not have been representative of that of an established sward.

When presenting the results of tests of significance in tables and figures, the conventional notation has been adopted:

NS not significant ($p > 0.05$)

* significant ($p < 0.05$)

** significant ($p < 0.01$)

*** significant ($p < 0.001$)

CHAPTER 4

THE AVAILABILITY OF SLUDGE N

The purpose of the examination of the effect of the treatments on N yield was to estimate the proportion of N in the sludges which becomes available to grass soon after application, to investigate the the effect of environmental variables on this availability and to determine the rate of release of N from the sludges. The fate of N applied to the grass in AN, LDS, LAS and PC was determined from the analysis of sludges and grass during the trial and from the analysis of soil samples taken at the end of the trial.

The N yield results were initially analysed by a two - way analysis of variance to obtain an error mean square based on as large a sample as possible. Coefficients of variation were also calculated and were found to be higher at Site B than at Site A in all site/cuts except cut 1, 1980.

The N yield results were split into the three components (Table 10) for presentation and analysis.

4.1 Component 1

4.1.1 Results

The relationship between N yield and the amount of N applied as AN, LDS and LAS is shown in Fig 10 to 19

A two - way analysis of variance of the component 1 treatment effects found a significant ($p < 0.05$) difference between the N source effects in all cuts at Site A except cut 1, 1980 and in all cuts at Site B except cut 3 and 4, 1979. The significance of the difference between individual N source effects was determined by Tukey's W procedure (Table 13). This found the effect of the AN to be significantly ($p < 0.05$) greater than that of the liquid sludges in

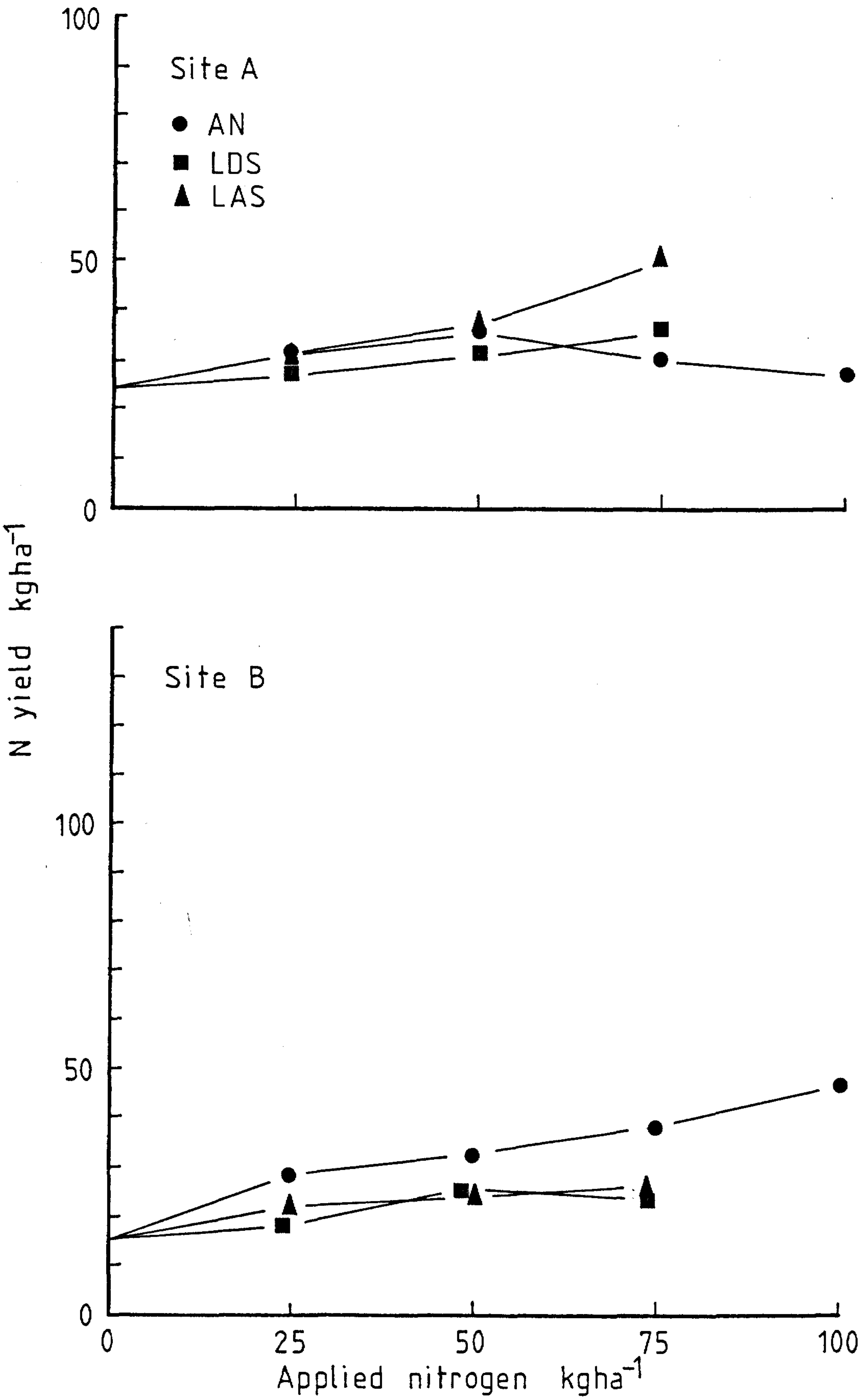


Fig 10 The relationship between N yield and applied nitrogen in cut 1, 1979.

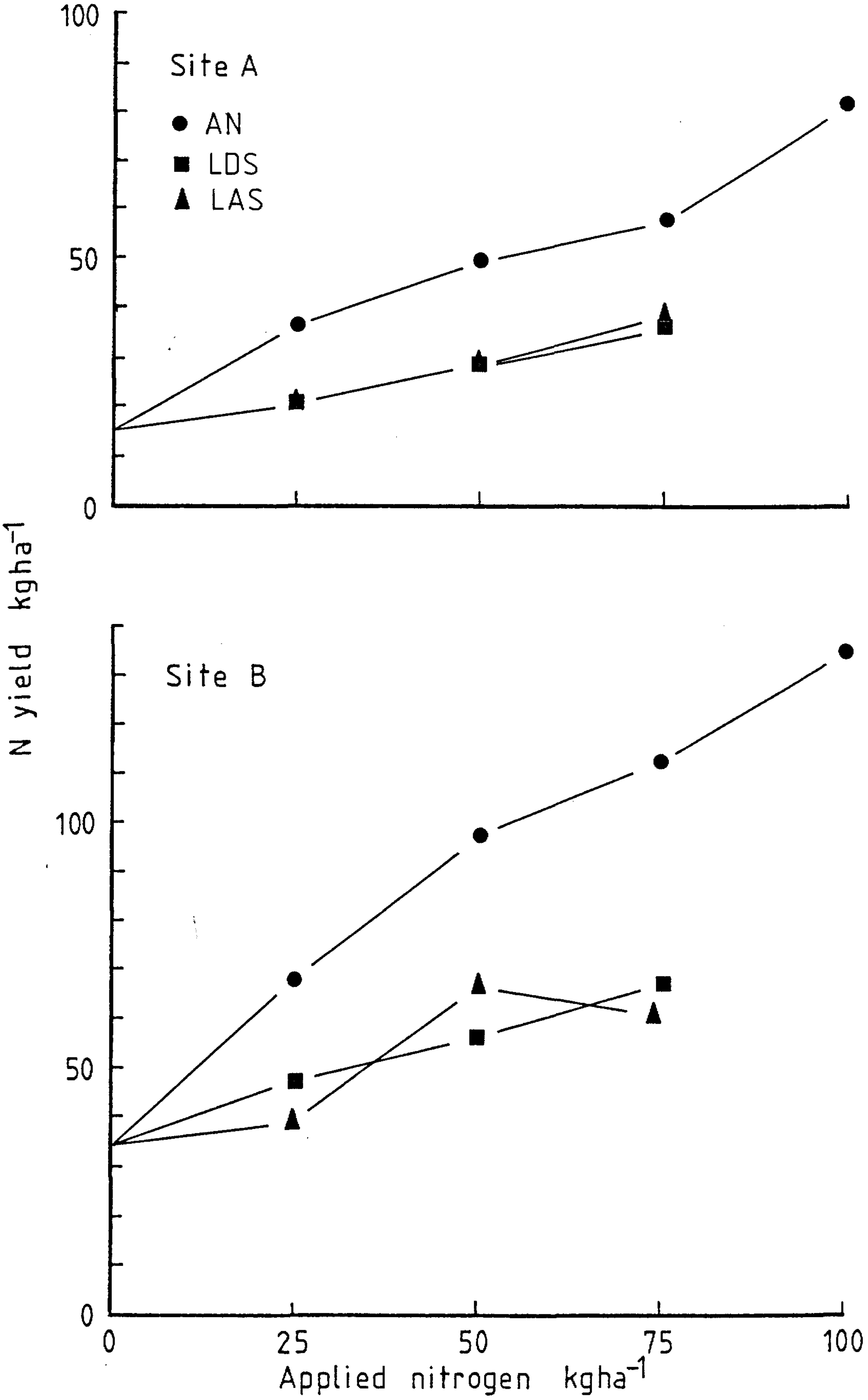


Fig 11 The relationship between N yield and applied nitrogen in cut 2, 1979.

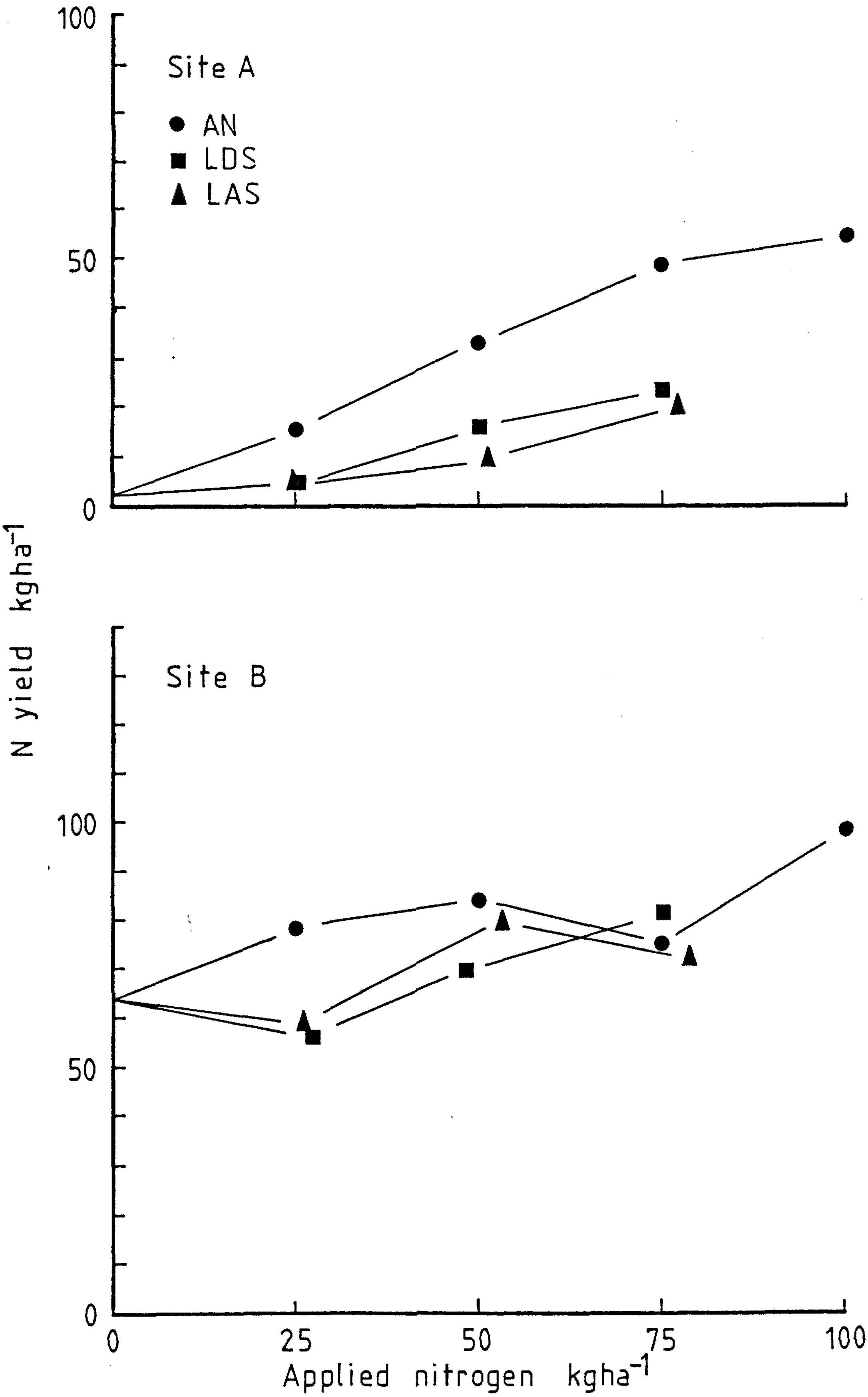


Fig 12 The relationship between N yield and applied nitrogen in cut 3, 1979.

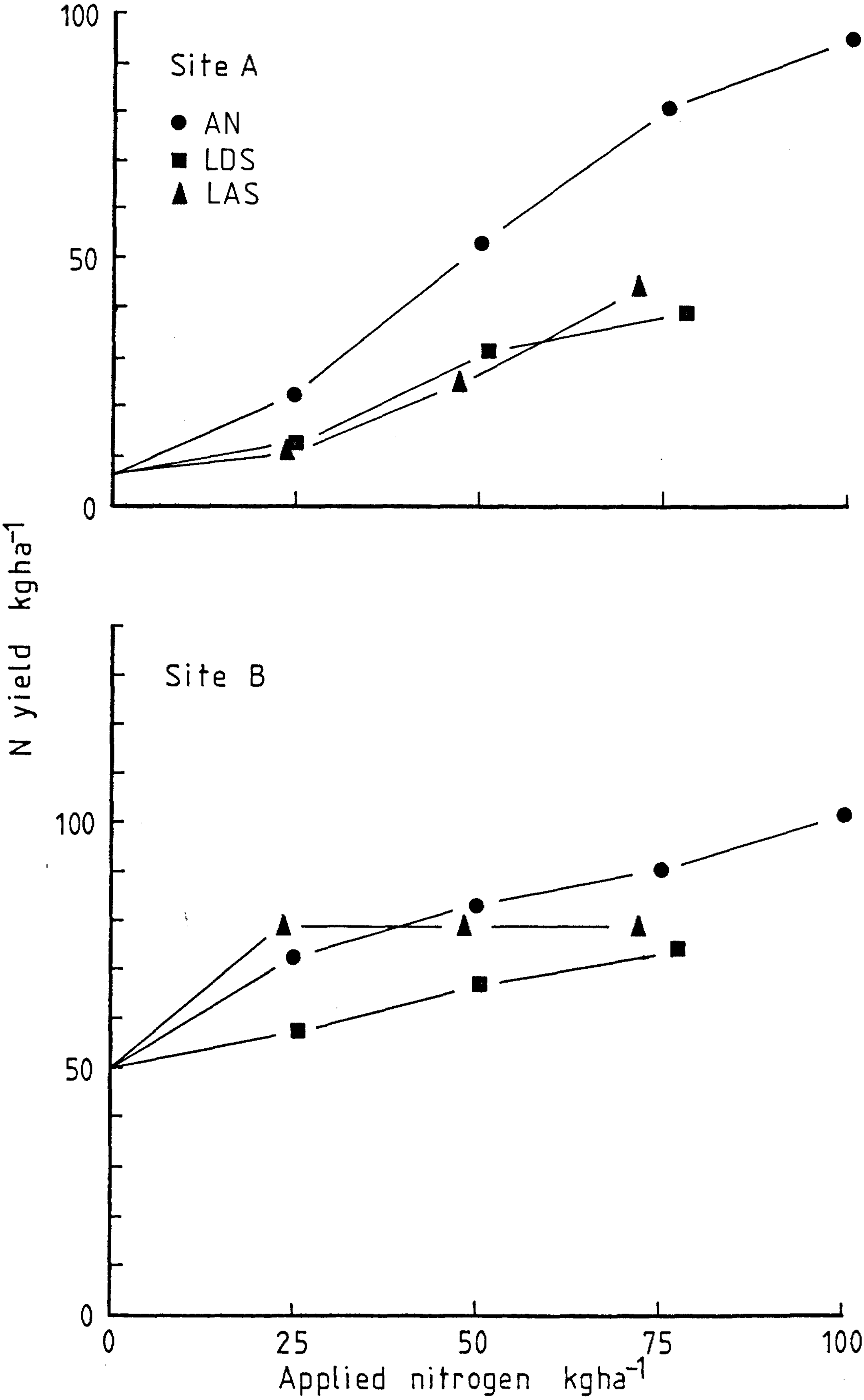


Fig 13 The relationship between N yield and applied nitrogen in cut 4, 1979.

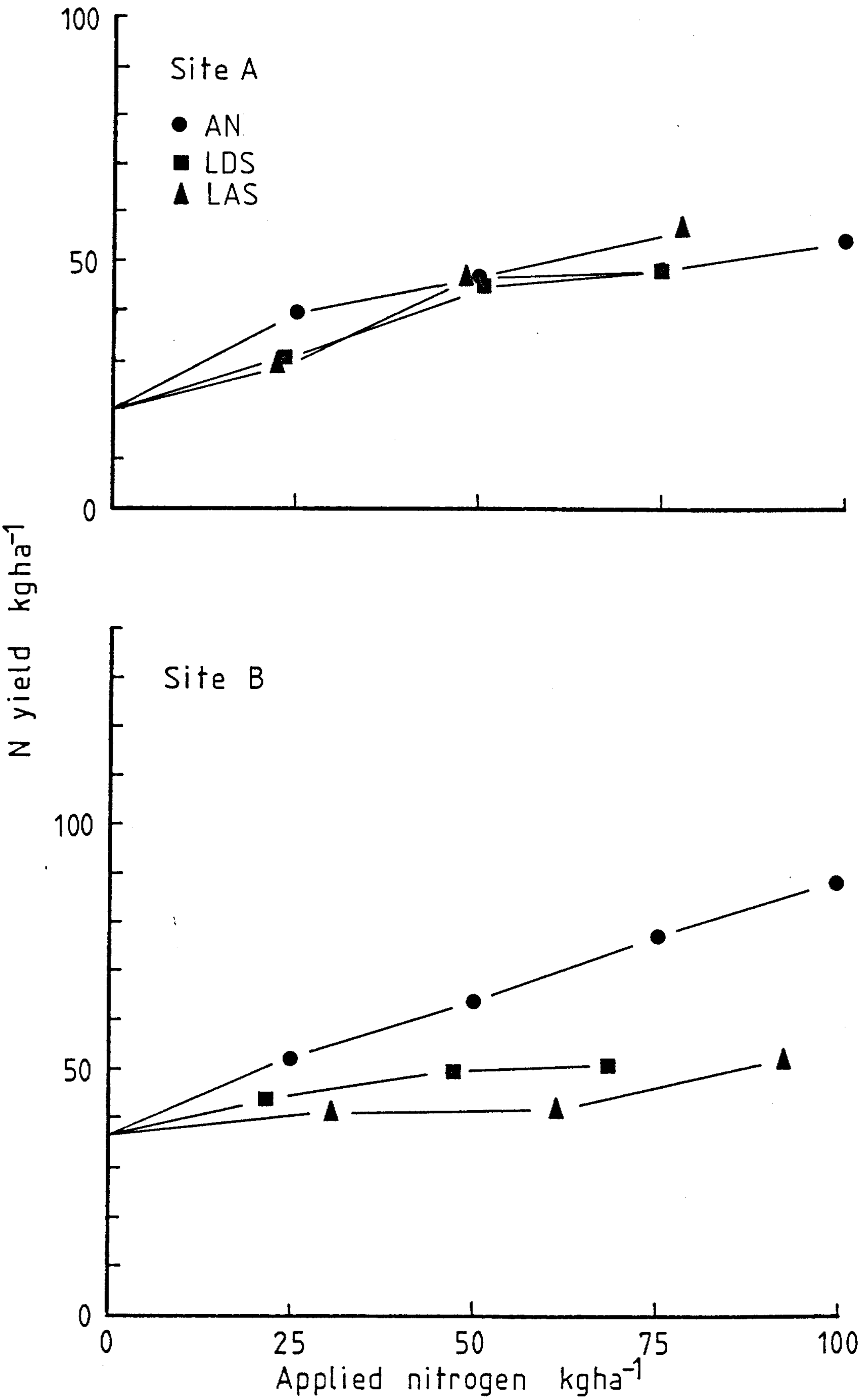


Fig 14 The relationship between N yield and applied nitrogen in cut 1, 1980.

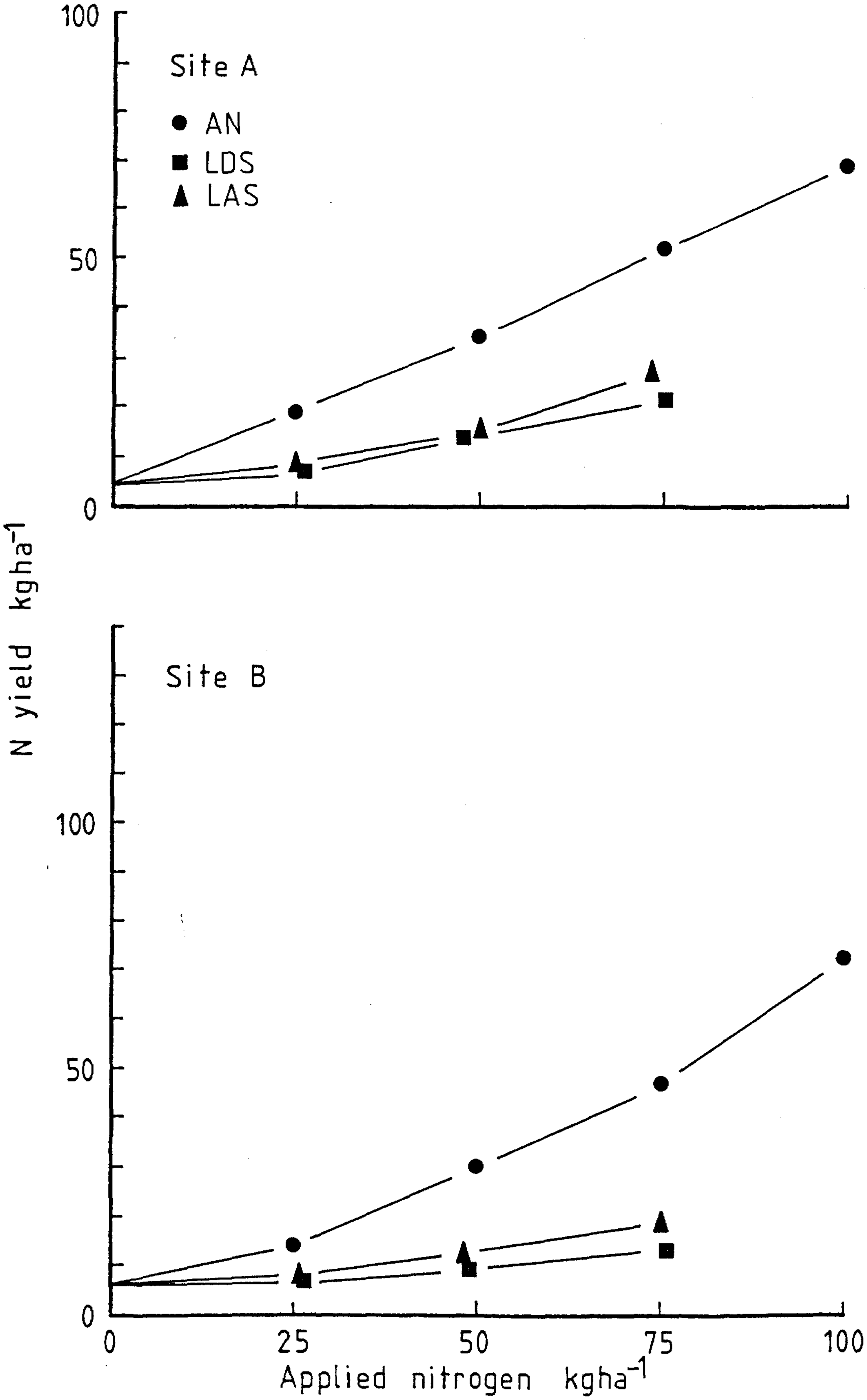


Fig 15 The relationship between N yield and applied nitrogen in cut 2, 1980.

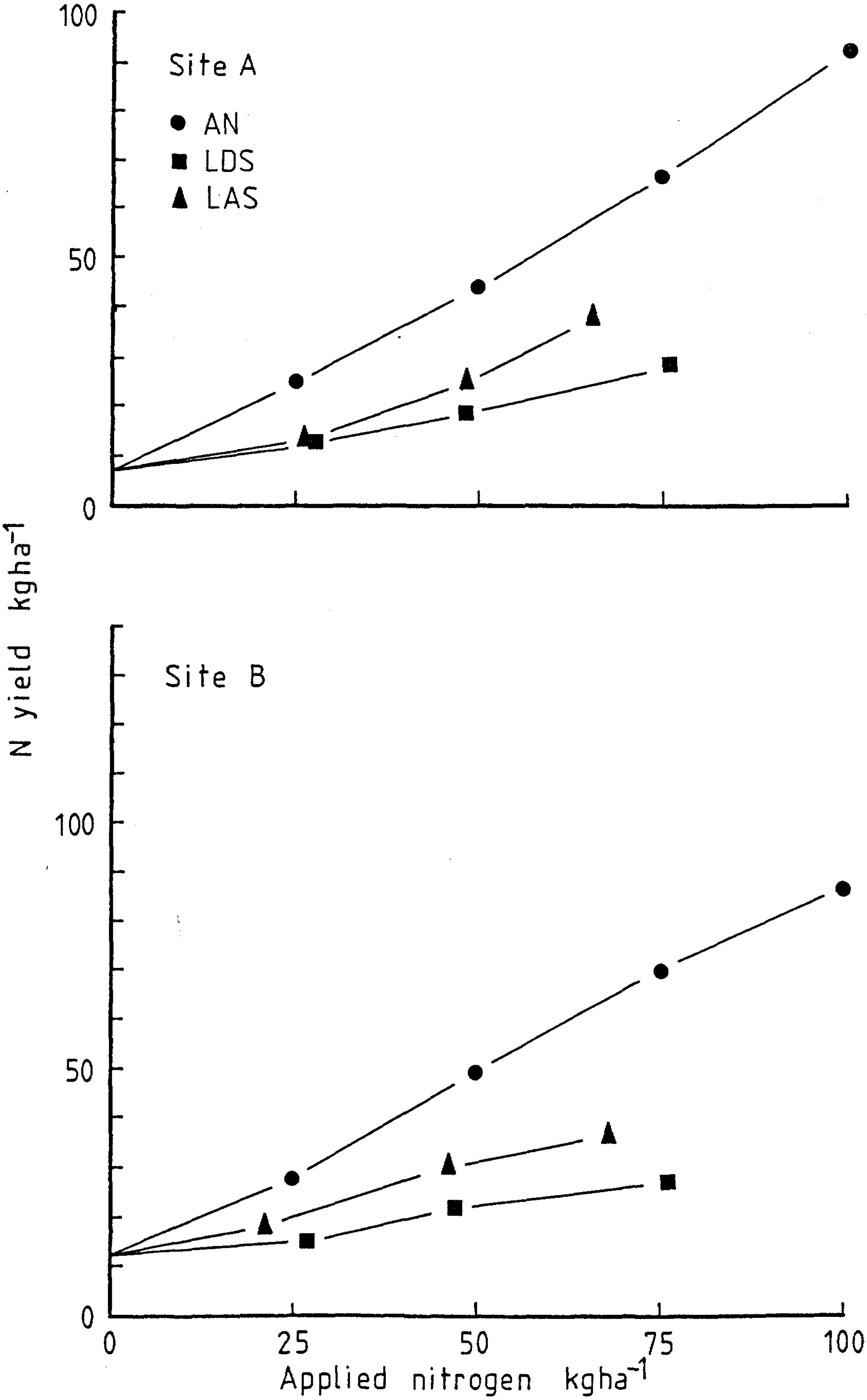


Fig 16 The relationship between N yield and applied nitrogen in cut 3, 1980.

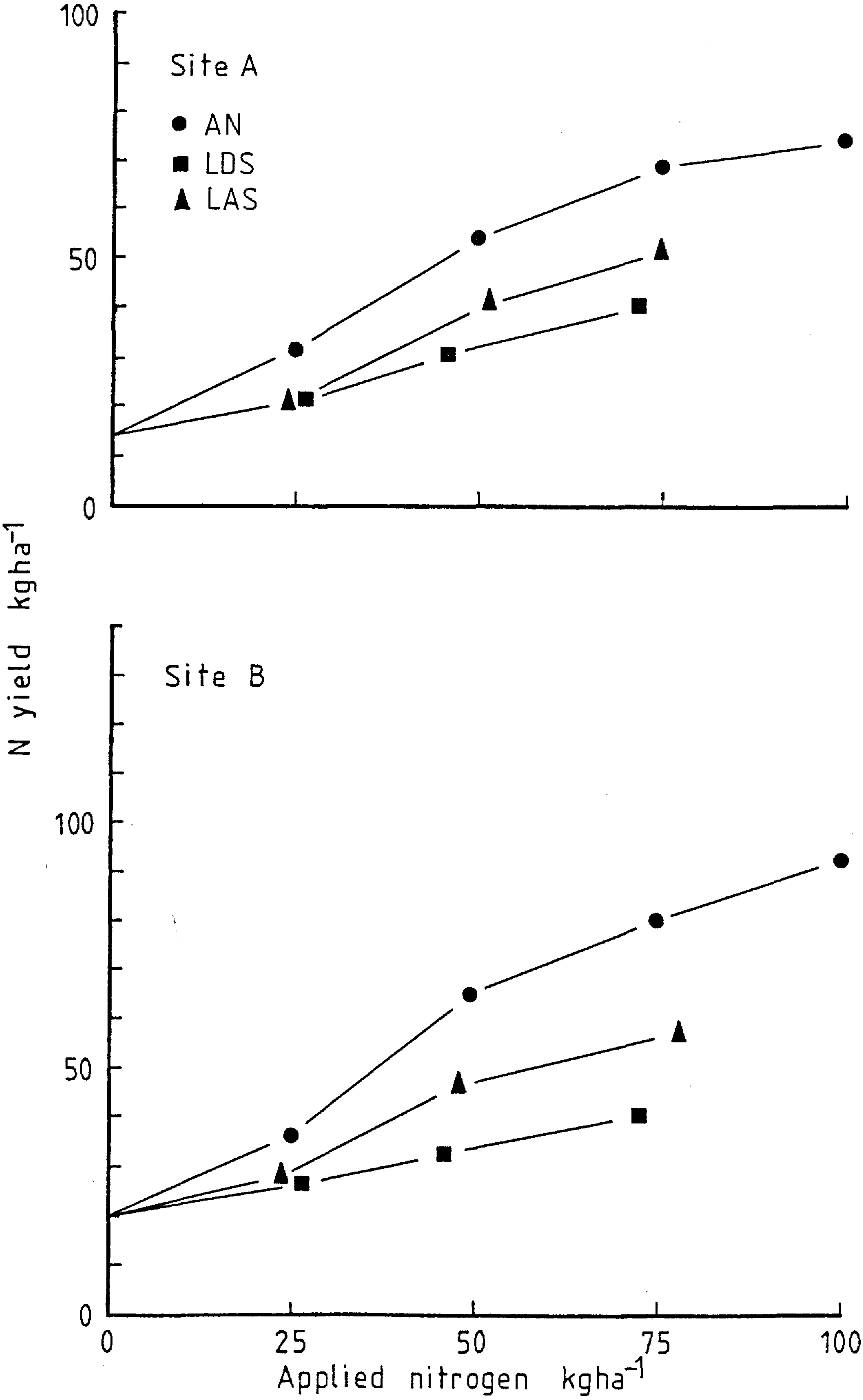


Fig 17 The relationship between N yield and applied nitrogen in cut 4, 1980.

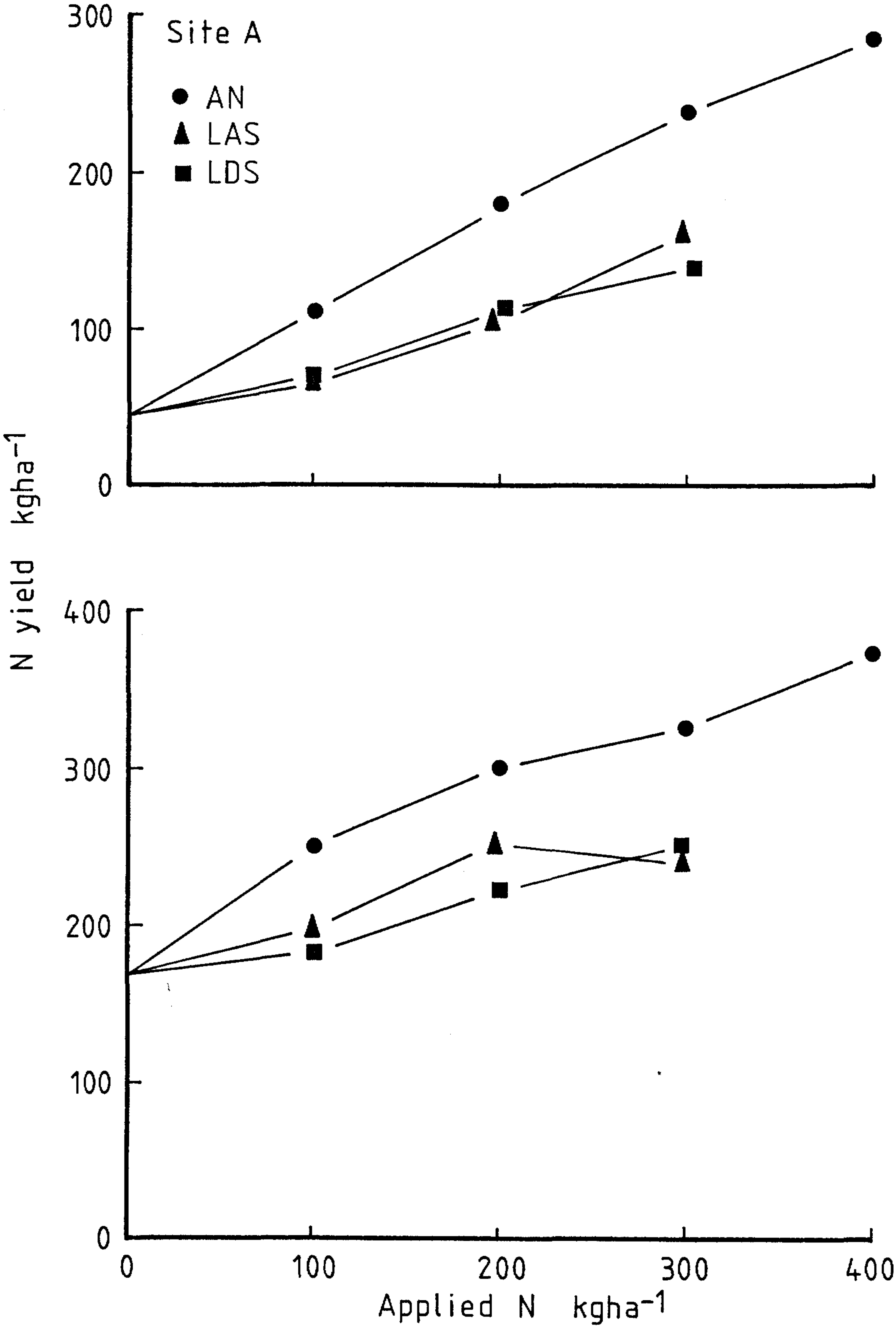


Fig 18 The relationship between the annual N yield and applied N in 1979.

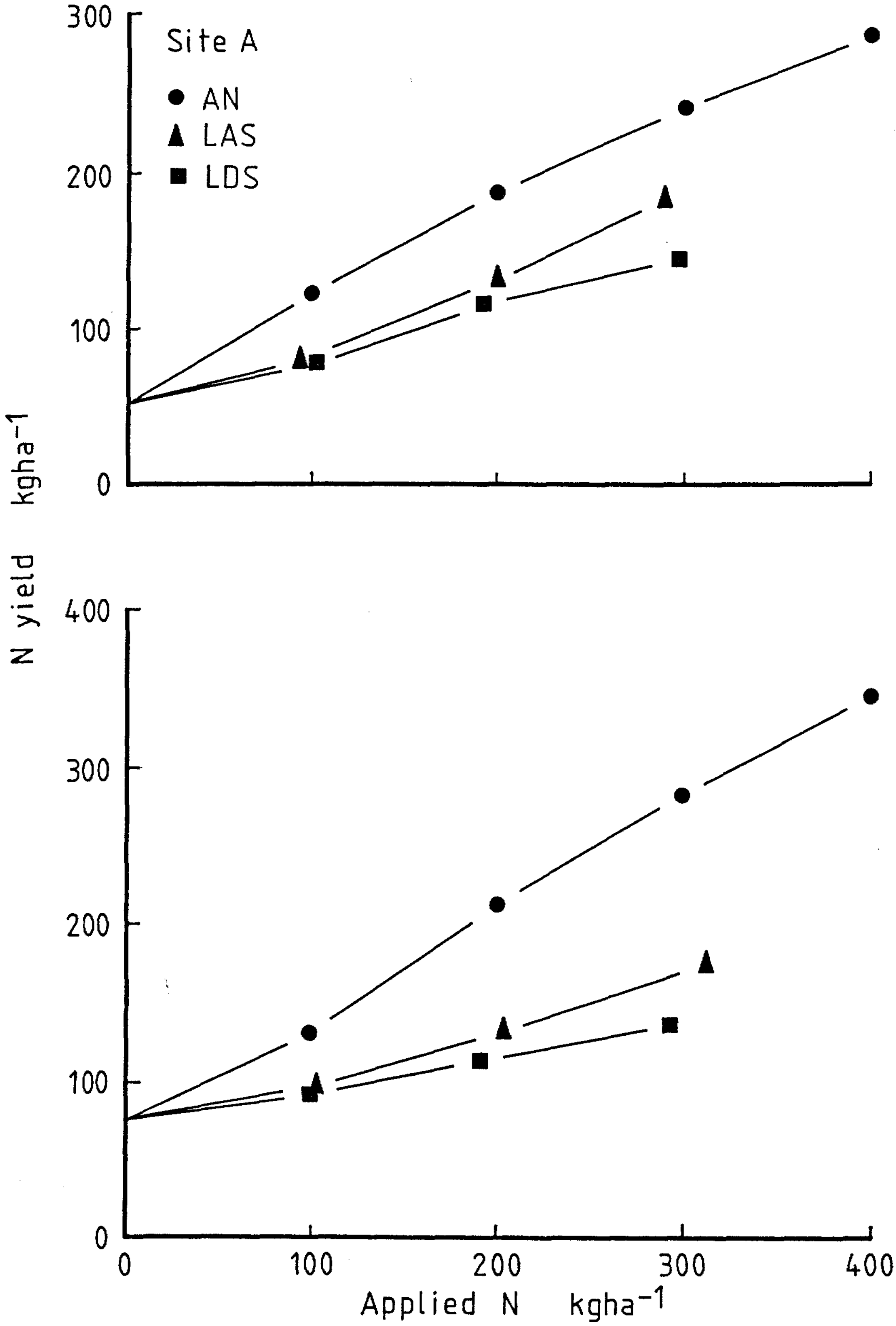


Fig 19 The relationship between the annual N yield and applied N in 1980.

Table 13 The Significance of the Differences between the Effects of Sources of N on N yield

	Cut	Site A			Site B		
		Increasing N Yield →					
1979	1	LDS	AN	LAS	LAS	LDS	AN
	2	LDS	LAS	AN	LAS	LDS	AN
	3	LAS	LDS	AN		NS	
	4	LAS	LDS	AN	LDS	LAS	AN
Total		LDS	LAS	AN	LDS	LAS	AN
1980	1		NS		LAS	LDS	AN
	2	LDS	LAS	AN	LDS	LAS	AN
	3	LDS	LAS	AN	LDS	LAS	AN
	4	LDS	LAS	AN	LDS	LAS	AN
Total		LDS	LAS	AN	LDS	LAS	AN

Source effects not underlined by a common line are significantly different ($p < 0.05$) as determined by Tukey's W procedure.

NS Source effect not significantly ($p > 0.05$) different by analysis of variance.

most site/cuts and in all site years although the effect of the AN was significantly ($p < 0.05$) lower than that of the LAS and not significantly ($p > 0.05$) different from that of the LDS in cut 1, 1979 at Site A. In those site/cuts and site/years in which there was a significant ($p < 0.05$) diffference between the effect of the sludges, the effect of the LAS was greater than that of the LDS.

A response analysis found a significant ($p < 0.05$) positive response to applications of AN in all site/cuts, to applications of LDS in all site/cuts except cut 3 and 4, 1979 and cut 2, 1980 at Site B and to applications of LAS in all site/cuts exept cut 3, 1979 at Site B (Table 14). The responses were predominantly linear in most site/cuts although non linear components were often significant ($p < 0.05$) at Site A. The non linear components were associated with the following features:

1) a reduction in the rate of response at high rates of application of AN. Examples are in cut 1, 1979 and cut 4, 1980 at Site A (Fig 10 and 17).
2) an increase in the rate of response with increasing rate of application of LDS and LAS when the N yield from the control plots was low. An example is in cut 4, 1979 at Site A (Fig 13).

At Site A the effect of these non linear components carried through into the annual yield response in both years. At Site B there were no significant ($p < 0.05$) non linear components in the response to any of the N sources in any cut or year.

It was originally intended to obtain estimates of the apparent N recoveries of AN, LDS and LAS from linear regressions of N yield on application rates 1 to 3 and then to compare the apparent recoveries of the sludge N with that of the AN to obtain estimates of the availability of the sludge N. However the response analysis suggested

Table 14 The Analysis of the Response of N yield to Applications of AN, LDS and LAS

Source	Component	Cut No								Total	
		1		2		3		4			
		Site									
		A	B	A	B	A	B	A	B	A	B
		1979									
AN	LIN	NS	***	***	***	***	*	***	***	***	***
	QUAD	**	NS	NS	NS	**	NS	NS	NS	*	NS
	CUBIC	NS	NS	NS	NS	**	NS	***	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	**	*	***	***	***	NS	***	NS	***	**
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	*	NS	**	NS	*	NS
LAS	LIN	***	*	***	***	***	NS	***	*	***	**
	QUAD	NS	NS	NS	NS	**	NS	**	NS	**	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	***	NS
		1980									
AN	LIN	***	***	***	***	**	***	***	***	***	***
	QUAD	NS	NS	NS	***	NS	NS	**	NS	*	NS
	CUBIC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	***	*	***	NS	***	**	***	***	***	***
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	***	NS
LAS	LIN	***	*	***	**	***	***	***	***	***	***
	QUAD	NS	NS	*	NS	*	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	***	NS

that this would not give a valid estimate of the sludge N availability due to the reduction in the rate of N yield response with increasing rate of application of AN which occurred at Site A and possibly at Site B. The estimates of the availability of the N in the sludges in each growth period and year were therefore obtained by comparing the amount of sludge and AN N required to give the same N yield (Table 15). The amount of N required was calculated from a linear regression of N yield on N applied for each N source. To obtain an independent estimate of the amount of sludge N required, the C treatment was not included in these regressions. All except five of the regressions were significant ($p < 0.05$). Of these five, the regression of LDS N on N applied in cut 4, 1979 at Site B was included as it was significant ($p < 0.05$) if tested against the mean square of the deviations from the regression instead of the error mean square and the regression of N yield on LDS N applied in cut 2, 1980 at Site B was also included as it was considered to have biological if not statistical significance. The arbitrary N yield value was chosen to be the mean of the LDS2 and LAS2 treatment effects as this placed it close to the mean effect of each sludge where confidence in the regression was greatest. The regression of N yield on AN N applied was based on the three treatments with effects closest to the arbitrary N yield value. This meant that in each case the regression for AN was based on the C, AN1 and AN2 treatments.

Due to the unusual response to AN in cut 1, in both years at Site A it was necessary to combine the results from cut 1 and 2 in both years at this site (p64).

The mean square of the deviations from the regressions of N yield on N applied and the error mean squares obtained from the two - way analysis of variance (p59) were tested for homogeneity using Bartlett's test. Homogenous mean squares were pooled for the determination of the standard deviations of the

Table 15 The Estimated Availability of LDS and LAS N.

Sludge	Site	Year	Cut number									
			1		2		3		4		Annual	
			ENA %	se	ENA %	se	ENA %	se	ENA %	se	ENA %	se
LDS	A	1979	42.0	1.5			40.2	1.2	51.5	2.0	45.4	0.9
		1980	45.7	3.0			35.7	1.9	47.2	2.3	46.8	1.1
		Mean									46.1	
	B	1979	31.7	0.8	32.6	7.7	ND	ND	45.7	4.8	37.4	3.2
		1980	48.7	4.7	19.7	1.4	28.0	1.6	34.5	2.8	31.6	1.8
		Mean									34.5	
LAS	A	1979	57.5	2.2			33.1	1.0	50.5	2.3	48.7	1.0
		1980	48.0	3.2			51.4	2.9	60.3	3.1	51.2	1.2
		Mean									50.0	
	B	1979	33.0	0.8	33.9	8.0	ND	ND	ND	ND	42.0	3.6
		1980	25.5	2.4	28.0	2.1	50.0	3.0	57.7	5.0	51.5	2.9
		Mean									46.8	

ENA = Estimated N availability se = standard error estimates of the amount of N required from each source to give the same N yield. The standard deviations of the estimates of sludge N availability were determined by the method described by Dahlberg (1940). It is acknowledged that computations based on these standard deviations may not be valid if the distribution of the comparison departed markedly from normality.

The estimated availability of the LDS N at Site B was significantly ($p<0.05$) lower than at Site A in both years by a t test (Table 15). The estimated availability of the LAS N at Site B was significantly ($p<0.05$) lower than at Site A by a t test in 1979 but there was no significant ($p>0.05$) difference between the sites in 1980.

The estimates of the availability of the sludge N in each cut were tested for correlation within each site against the following factors:

1) Percentage solids in sludge (LDS only)
2) Percentage sludge N as NH_4^+-N (LDS only)
3) Rainfall
4) 10 cm soil temperature
5) Mean soil moisture content
6) Cut number

Factors 3, 4 and 5 were tested as the daily mean over the whole growth period and as the daily mean over the first 14 days to detect both short and longer term effects of the environmental factors. A Spearman rank correlation test was used as the estimates of the availability of the sludge N were not thought to be homoscedastic. It is acknowledged that the estimates of availability were not wholely independent due to the residual effects of one application on the primary effects of the next. It was considered unlikely that such residual effects led to spurious correlations but true associations may have been masked.

There was a significant ($p<0.05$) negative correlation between the estimated availability of the LDS N and the mean rainfall over the whole growth period at Site A (Fig 20) and both the mean rainfall and soil moisture content over the first 14 days at Site B (Fig 20 and 21). The availability of the LAS N was not significantly ($p > 0.05$) correlated with factors 3 to 5 over the first 14 days or the whole of the growth period at either site although there was a strong trend towards an increase in the estimated availability as the growth season progressed.

The availability of the LDS organic N was estimated by making the same assumptions as Magdoff and Amadon (1980). The estimated availability was lower at Site B than at Site A in both years (Table 16). In the second growth period of 1980 at Site B the estimated availability of the LDS N was significantly ($p < 0.05$, by a t test) less than that predicted from the amount of NH_4^+-N applied.

The estimates of the availability of the LDS organic N were tested for correlation against environmental factors 3 to 6 (see above) using a Spearman rank correlation. A significant ($p < 0.05$) negative correlation was found between the estimated availability of the LDS organic N and mean rainfall over the first 14 days of the growth period (not shown). No other significant ($p > 0.05$) correlations were found.

4.1.2 Discussion

The N yield response

The results indicate that the availability of the N in the sludges was below that in the AN whilst there was little difference between the availability of the N in the two liquid sludges (Table 15). The similarity of the availability of the N in the liquid sludges was probably coincidental as previous investigations have found the availability of the N in both sludges, but particularly the LDS, to vary over a wide range (Table 5)

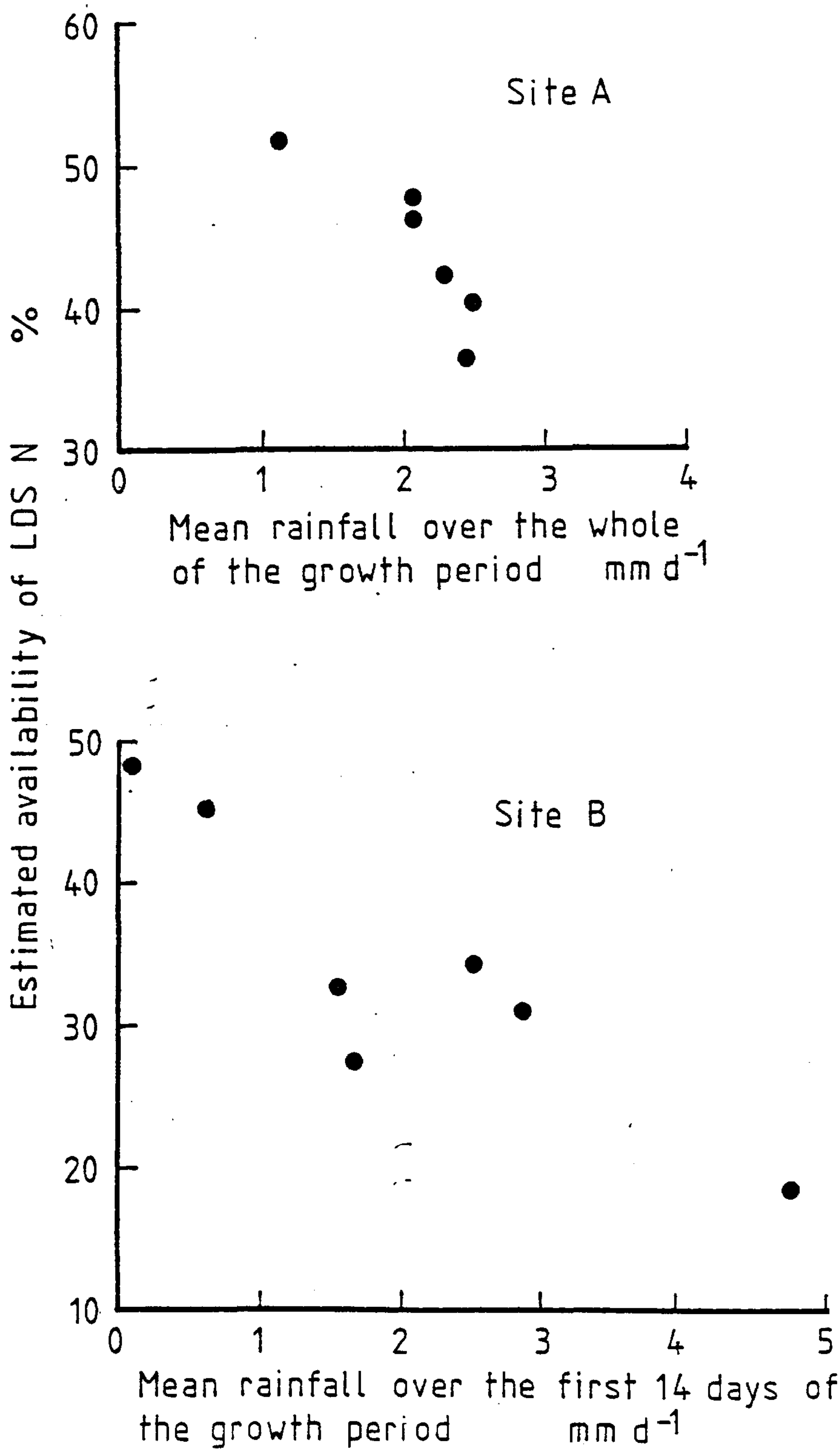


Fig 20 The relationship between the estimated availability of LDS N and rainfall.

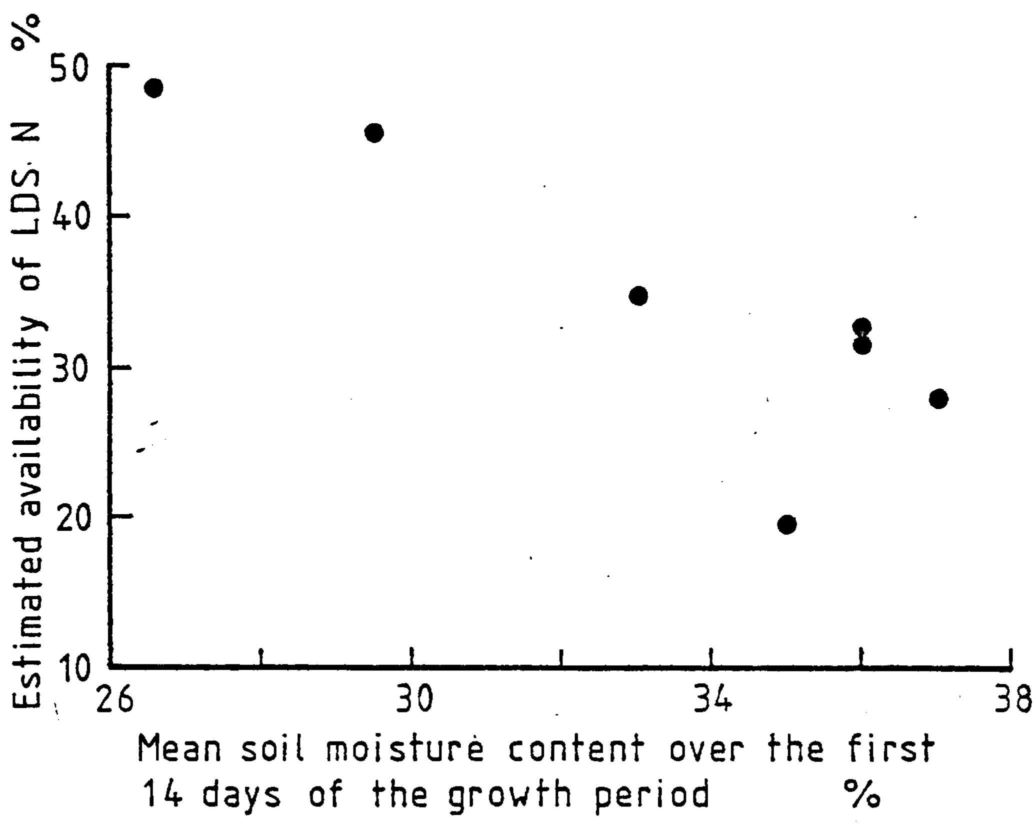


Fig 21 The relationship between the estimated availability of the LDS N and the mean soil moisture content over the first 14 days of the growth period at Site B.

Table 16 The Estimated Availability of the LDS Organic N

		Estimated availability %				
		Cut number				
Site	Year	1	2	3	4	Annual
A	1979	21.9		2.6	29.7	21.7
	1980	18.5		12.5	28.2	20.3
	Mean					21.0
B	1979	2.8	8.2	ND	21.3	8.4
	1980	18.2	-14.2	2.0	10.9	2.3
	Mean					5.4

It is likely that the absence of significant ($p < 0.05$) non linear components in the response of the N yield to the application of the N sources at Site B reflects the higher variability of the results at this site in comparison with Site A (p 59). The description of the response to N given below is probably valid at both sites.

The response of the N yield to the application of the N sources can best be explained if the response to the total N supply is assumed to be similar to the logistic type response described by Whitehead (1970). This suggests that when the supply of N from the soil is very low, small applications of available N are predominantly retained in the soil or stubble, leading to low N yield responses. As the supply of available N increases, a greater proportion of the N is recovered in the grass crop. The response of the N yield is therefore markedly non linear at low rates of application of available N but becomes nearly linear as the rate of application increases. When the supply of N from the soil is moderate, the non linear component is absent. This type of response would account for the presence of non linear components in the response to LDS and LAS when the N supply from the soil was low (eg cut 3 and 4, 1980 at Site A) but not when it was moderate (eg cut 1, 1980 at Site A). The absence of such non linear components in the response to AN was probably due to the greater availability of the N in this source.

Whitehead (1970) suggested that when the total N supply is high, the efficiency with which the N is absorbed by the grass is reduced. This may account for the reduction in the rate of response of the N yield which often occurred at high rates of application of AN (eg cut 4, 1980 at Site A) and the poor response to all sources of N in growth periods in which the supply of N from the soil was high (eg cut 3 and 4, 1979 at Site B). However the reduction in the rate of response at high rates of application of AN in cut 1 in both years at Site A was probably due the selective winterkill which occurred at this site. The winterkill increased with increasing rate of application of AN and was evident before the first application of the year was made. This suggests that there was an interaction between the winterkill and the residual effects of the applications made in the previous year. Although the sward receiving high rates of application of AN at Site B became open and tussocky at the end of the growing season, there was no marked deterioration over the winter. The difference in altitude between the two sites may have been partly or wholely responsible for this difference in winterkill.

The substantial winterkill at Site A raises the possibility that there may have been insufficient viable tillers remaining on the plots to absorb all the AN N applied in the first application of the year. However the good response to AN in cut 2 in both years at this site suggests that some or all the AN N applied for the first growth period was recovered in the second. The examination of the fate of N applied in the three sources (p 72) concluded that little N applied to Site A was lost from the soil by leaching. The see-saw effect in the response to the AN made it necessary to combine the results from cut 1 and 2 at this site for the examination of the within site variations in the estimated availability of the N in the sludges.

The availability of sludge nitrogen

The estimated availability of the LDS N in this trial (Table 15) was lower than found in field trials by other investigators in the UK (Coker, 1966a, Thomas, 1981, Edgar, 1981). This was probably due mainly to the lower NH_4^+-N content of the sludge used in this trial. The estimated availability of the LAS N was lower than found by Magdoff and Amadon (1980) but similar to that found by O'Riordan (pers. comm). Some variation in the availability of the N in LAS's from different STW's would be expected due to variations in the treatment processes (p 11).

The results of the trial suggest that the availability of the LDS N was lower on the clay soil than on the sandy loam (Table 15) and that this was due to a lower availability of the LDS organic N on the clay soil (Table 16). A reduction in the mineralization of sludge organic N due to an interaction between the organic matter and the clay similar to that found by Guckert et al (1976) is unlikely to have occurred as the N balance at the end of the trial failed to detect a greater accumulation of LDS N in the clay soil than in the sandy soil (Table 20). The large discrepancy in the LDS N balance plus the appearance of a negative value for the estimated availability of the LDS organic N in cut 2, 1980 suggests that there was a loss of N following the application of LDS to the clay soil. The loss of N by leaching from soil under grass has been found to be minimal except under extreme weather conditions (Garwood and Tyson, 1973a and 1977) and would anyway be unlikely from such a poorly drained site. It is more likely that the losses were gaseous. These could have occurred by:

1) the volatilization of NH_4^+-N as NH_3
2) enhanced denitrification of soil NO_3^--N due to the addition of biodegradable sludge organic matter during periods of wet weather.
3) the mineralization and nitrification of sludge-N at the soil surface followed by denitrification further down the soil profile

The soil conditions at Site B (moist, high CEC) in comparison with Site A (drier, lower CEC) would have been expected to favour a greater loss of NH_3 from the latter site (Terman, 1979). However, the poor drainage at Site B probably reduced the rate at which the sludge liquid fraction percolated into the soil and this may have led to increased volatilization from this site during dry weather. The denitrification of soil or sludge N may have occurred given the poor drainage and the proximity of the water table to the soil surface (Table 9). This latter hypothesis is further supported by the negative relationship between the estimated availability of the LDS N and the rainfall and mean soil moisture over the first 14 days after application (Fig 21).

The negative relationship between the estimated availability of the LDS N and mean rainfall over the whole growth period at Site A (Fig 20) is unlikely to have been due to a loss of N by denitrification as the N balance found the recovery of LDS N in grass and soil to be complete (Table 20). This suggests that the rainfall led to increased net immobilization of N in the soil. Although rainfall might have been expected to stimulate the decomposition of the LDS organic matter by relieving dehydration at the soil surface, the C:N ratio of this fraction (11.4:1) was too narrow to suggest that this gave rise to net immobilization. The absence of a similar relationship with soil moisture and the lack of an adequate mechanism by which the rainfall could act on the LDS N may indicate that the correlation arose by chance.

The absence of significant ($p < 0.05$) correlations between the availability of the LDS N and other factors tested is not surprising given the small number of observations and is not considered by the present author to contradict the relationships found by other investigators (Miller, 1974, Furrer and Bolliger, 1978, Terry et al, 1978, Edgar et al, 1981, Hsieh et al, 1981b).

Enhanced denitrification similar to that described above may have been responsible for the lower availability of the LAS N on the clay soil in 1979 although a larger and more consistent effect would have been expected given the biodegradability of the LAS organic matter (p 16). The absence of any relationship between the estimated availability of the LAS N and the rainfall, soil moisture or temperature is not surprising given the small number of observations. There appeared to have been a cumulative effect of the residual action of the LAS in the 1980 growing season although this was not significant ($p > 0.05$). This trend may have masked any effect of the other factors.

The annual estimates of the availability of the LDS organic N at Site A were greater than reported by Thomas (1981), similar to that reported by Edgar et al (1981) but lower than reported by Furrer and Bolliger (1978) and found in most incubation experiments (Table 4). It is possible that the higher values reported from pot and incubation experiments reflect the higher temperatures at which these experiments were conducted. It is also possible that some field trials may lead to an underestimation of the true availability of the LDS organic N due to the loss of N by volatilization or denitrification (see above). As it is likely that such gaseous losses occurred at Site B, the estimated availability of the LDS organic N is probably erroneous and neither it nor the relationship between it and the environmental factors are discussed further.

Little is known about the gaseous loss of N from surface applied liquid sludges under UK environmental conditions. The magnitude and factors affecting these losses needs to be known to enable investigators to fully interpret the results of fertilizer experiments with sludges and to enable sludge users to adjust the application rate to ensure adequate fertilization.

Regardless of the origin, the variations in the estimated availability of the liquid sludge N suggest that these sludges are less reliable than AN as tools for the management of grass production. Although the variation in the estimated availability of the LDS N at Site A were small and in practice would probably not have been noticed by a farmer, the size of the variation at Site B (19.7% to 48.7%) was probably sufficient to reduce the value of the sludge to the farmer. Similarly the variation in the estimated availability of the LAS N at both sites (33.1% to 60.3% at Site A and 25.5% to 57.7% at Site B) would probably have resulted in a noticable loss of reliability.

4.2 Component 2

4.2.1 Results

The application of the W treatment did not significantly ($p < 0.05$) increase or decrease the N yield in comparison with the C treatment as determined by Tukey's W procedure (Table 17). The W + AN2 treatment significantly ($p < 0.05$) decreased the N yield in comparison with the AN2 treatment in cut 4, 1979 at Site A but increased it in cut 3, 1980 at the same site.

4.2.2 Discussion

As the W treatment did not significantly ($p < 0.05$) affect the N yield, the significant ($p < 0.05$) differences between the W + AN2 and AN2 treatments can be attributed to positive and negative N x H_2O interactions.

The growth periods in which the interactions occurred were not distinguished by high or low rainfall or soil moisture contents (Fig 5 and 6). Conversely, there were no significant ($p < 0.05$) interactions in cuts 1 and 2, 1980 when the water supply was low and high respectvely. This suggests that the N x H_2O interactions proposed by Coker (1979) did not occur in this field trial. The source of these interactions (if real effects) remains obscure.

The absence of any negative N x H_2O interactions at Site B does not rule out the possibility that the negative relationship between the availability of the LDS N and rainfall at this site (p 66) was due to enhanced denitrification. There was no available C applied in this

Table 17 The Effect of Component 2 Treatments on N Yield

Treatment	N yield kg ha^{-1}									
	Site									
	A					B				
	1	2	3	4	Annual	1	2	3	4	Annual
					1979					
W	24.4	16.9	1.8	6.9	50.0	18.3	25.1	53.1	62.6	159.1
C	24.6	15.3	2.4	6.0	48.2	14.7	35.2	65.4	52.1	167.4
Sign.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W + AN2	40.5	59.5	31.8	47.3	179.2	27.3	102.2	84.7	89.2	303.5
AN2	36.8	54.6	33.4	53.7	178.6	31.8	99.4	86.0	83.6	300.8
Sign.	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
					1980					
W	22.3	5.6	8.1	16.0	52.0	35.7	4.4	8.6	21.1	69.8
C	21.6	4.7	7.8	14.2	48.3	36.8	6.7	12.0	20.6	76.2
Sign.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W + AN2	54.9	34.6	52.3	60.1	201.9	72.1	30.4	50.3	65.8	218.5
AN2	49.1	35.3	44.6	54.3	183.2	65.1	30.1	49.5	66.0	210.7
Sign.	NS	NS	*	NS	NS	NS	NS	NS	NS	NS

Sign - the significance of the difference between the above treatments as determined by Tukey's W procedure.

treatment and it is unlikely that the small amount of water applied would have contributed substantially to the build-up of anaerobic conditions.

4.3 Component 3

4.3.1 Results

The apparent recovery of N from the component 3 treatments is given in Fig 22 and 23 and in Table 18. The significance of the differences between the component 3 treatment effects and that of the C treatment were determined by Tukey's W procedure.

The apparent recovery of N from the component 3 treatments was lower in 1979 than in 1980 and the percentage annual recovery of PC N was lower than that from the LDS and LAS. The rate of release of N from the liquid sludges was also greater than from the PC. The rate

Table 18 The Annual Apparent N Recovery from the Component 3 Treatments.

	Treatment					
	LDS(s)		LAS(s)		PC	
	Site					
	A	B	A	B	A	B
			1979			
Apparent N recovery %	21.5	6.2	30.7	19.6	5.0	24.0
Significance	**	NS	**	NS	NS	NS
% of annual N recovery in cut 1	50.0	ND	72.8	ND	ND	ND
			1980			
Apparent N recovery %	39.5	26.9	42.1	36.4	16.0	5.9
Significance	**	*	**	**	**	NS
% of annual recovery in cut 1	64.6	88.6	53.7	59.3	45.5	36.4

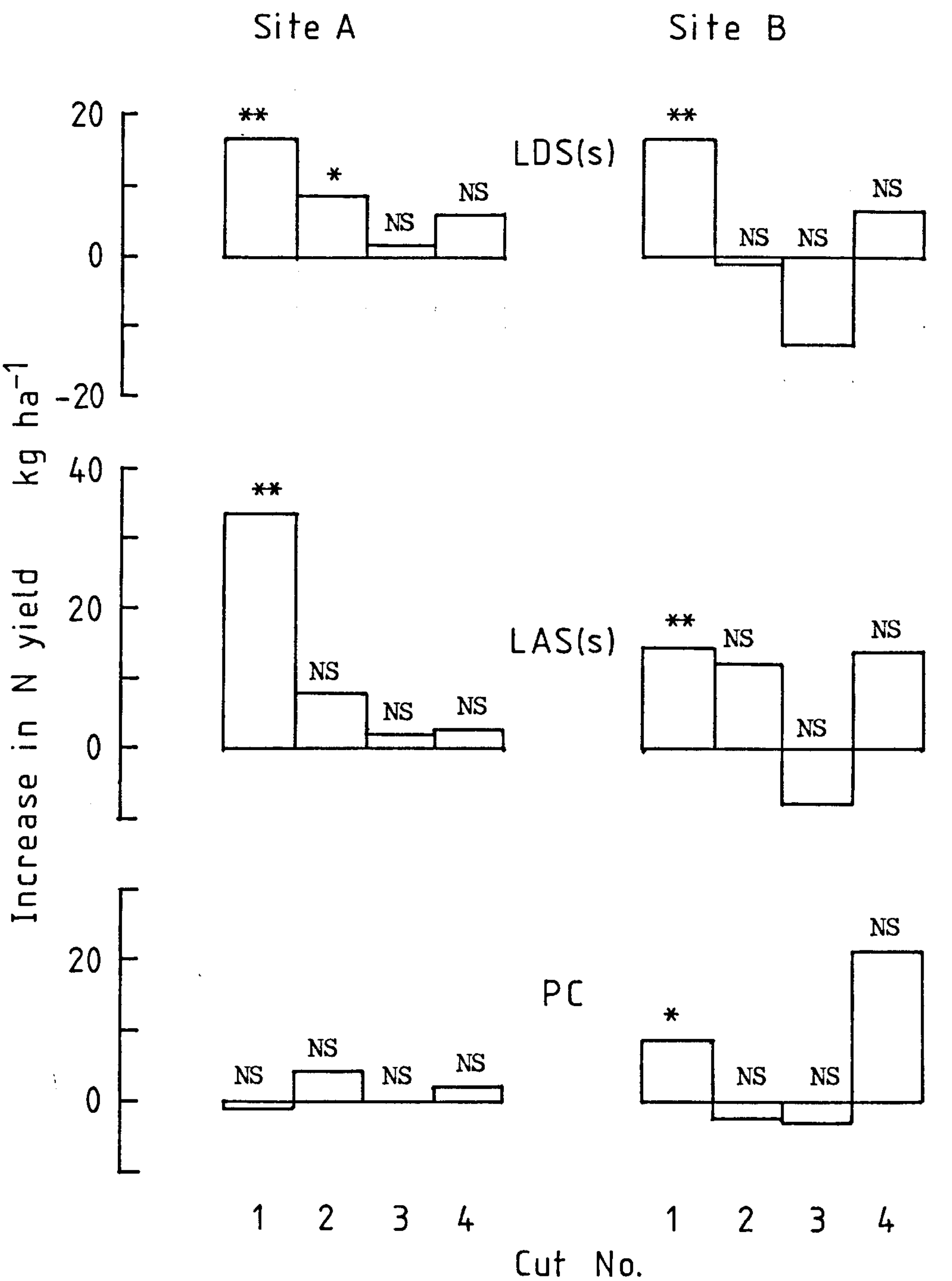


Fig 22 The increase in N yield due to the application of the Component 3 treatments in 1979.

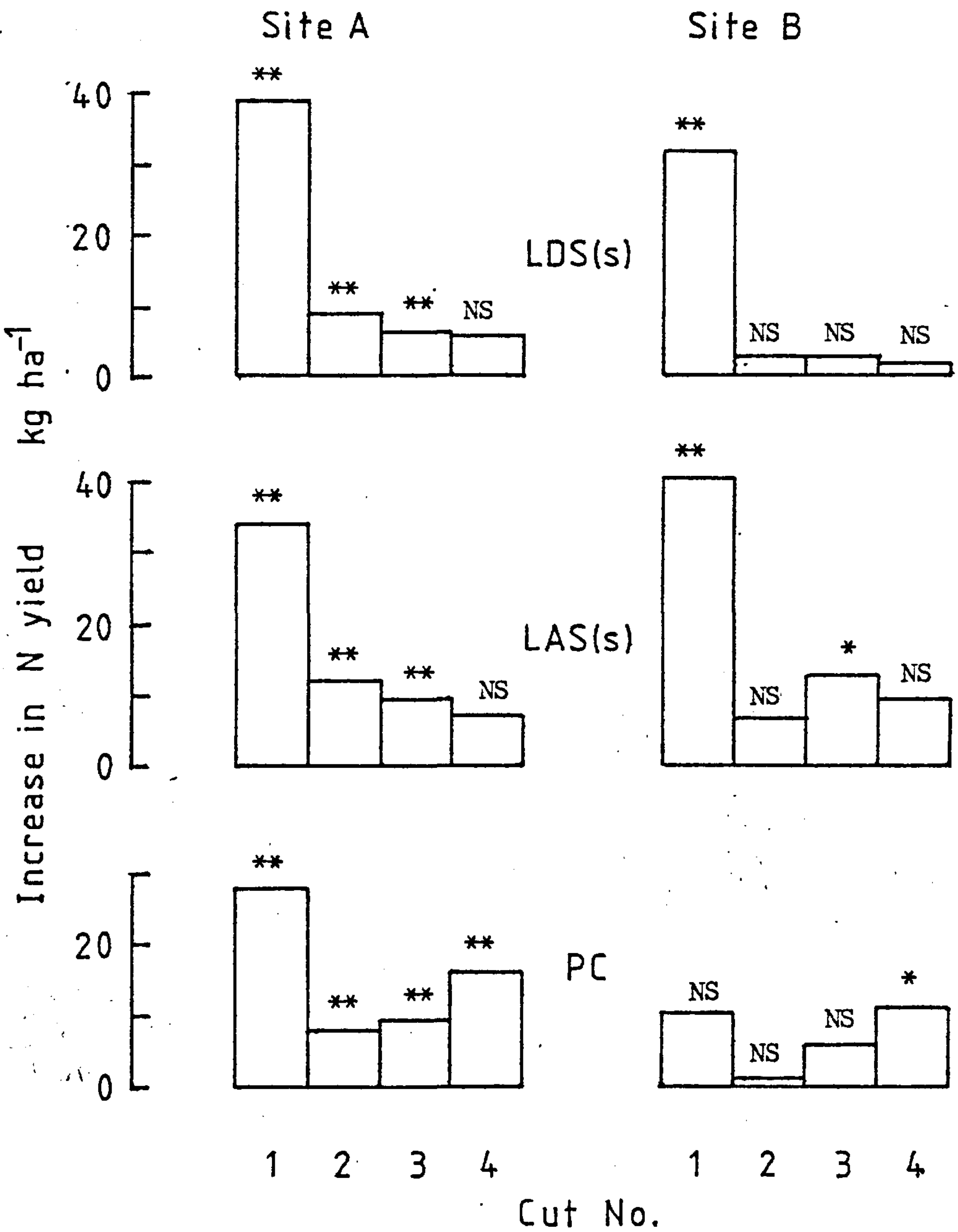


Fig 23 The increase in N yield due to the application of the Component 3 treatments in 1980.

of release of LAS and LDS N was similar in 1979 at Site A but the residual effect of the LAS was greater than that of the LDS in 1980 at both sites.

4.3.2 Discussion

The lower recovery of sludge N in 1979 compared to that in 1980 was probably due to the poor growing conditions in the spring of that year (Figs 4 and 5). The high spring rainfall may also have reduced the recovery of the sludge N by increasing the amount of denitrification.

The pattern of release of N from the sludges at Site B in 1979 (Fig 22) was altered by the delay in the application of treatments and disrupted by the high variability of the results (p 59). The greater residual effect of the LAS compared to that of the LDS in 1980 at both sites was probably due to the retention of the LAS solids at the soil surface and subsequent delay in the mineralization of organic N during the dry spring weather in this year (Fig 23). It is likely that there was a similar reduction in the mineralization of the LDS organic N but as much less of the readily available N in this sludge was in the organic form, the impact of the dry weather was smaller. A similar effect was observed in the response of the grass/clover sward to the spring application of the liquid sludges (p 130).

The evenness of the release of the PC N over the growing season probably contributed to the frequent lack of significant ($p<0.05$) differences between the effect of the PC treatment and that of the control. The persistence of the PC as lumps on the soil surface may have been a factor in the slow rate of release of this sludge (Fig 24 , Appendix 3).

As a single spring application of AN was not included in this trial, it is not possible to make a direct assessment of the availability of the PC N. However, if the annual apparent recovery of N from the AN1 treatment is assumed to be similar to that which would have been obtained from such a treatment then the availability

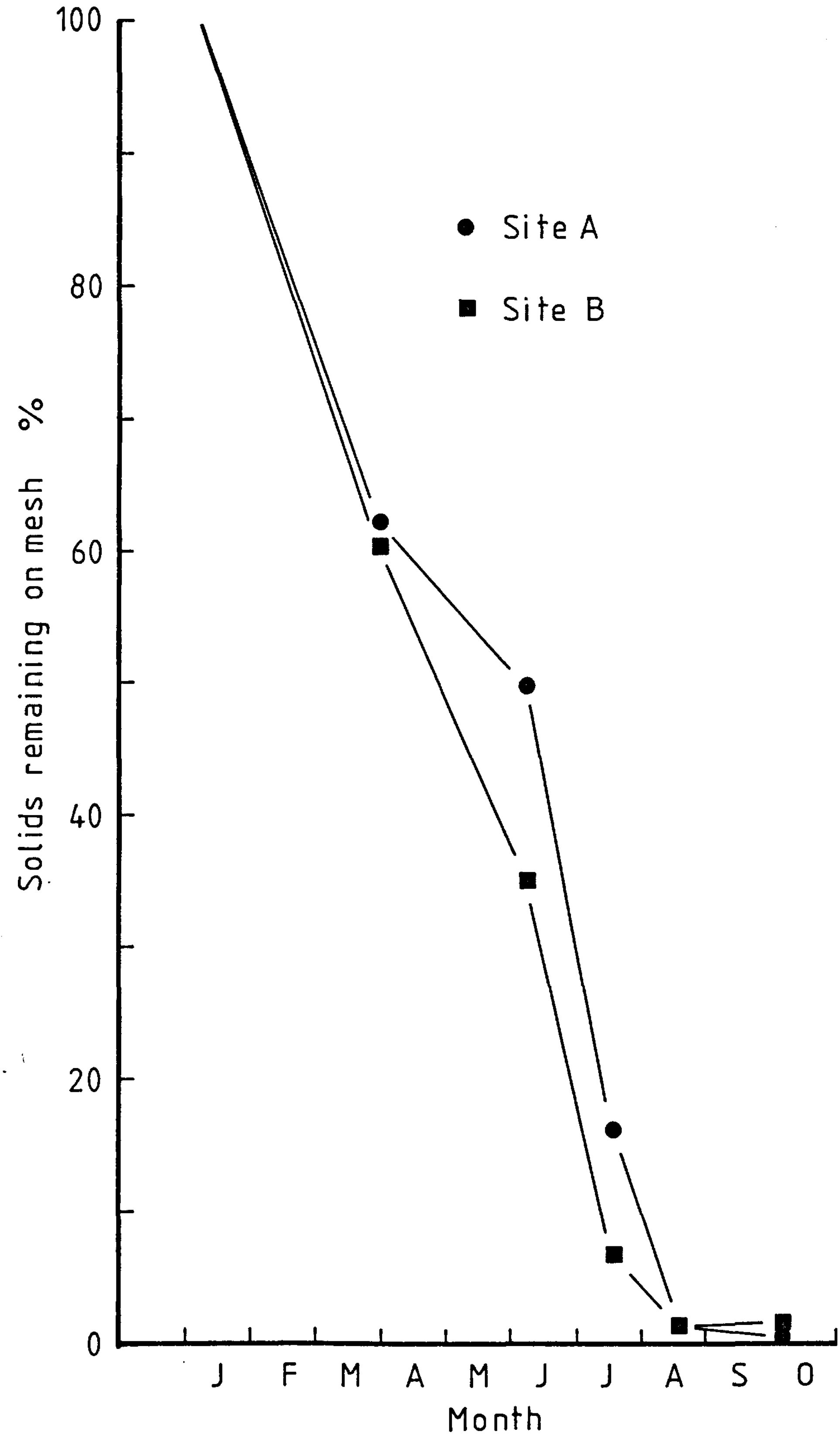


Fig 24 The breakdown of pressed cake solids following surface application in early January 1980.

of the PC N over the two years was about 16% at Site A and about 20% at Site B. These values are higher than the 15% availability of N in a dewatered digested sludge found by Coker (pers. comm.) but lower than the values reported by Bunting (1963). A greater availability of the N in a dewatered cosettled sludge than in a dewatered digested sludge would be expected as most of the readily available organic N is mineralized during digestion and lost during dewatering. The higher values obtained for the availability of the N in air dried activated and primary sludges found at Rothamsted may reflect the use of arable crops in these trials.

It is unlikely that the low recovery of PC N was due to the loss of N by denitrification or leaching as the recovery of PC N in the grass harvested and in the soil was complete at Site A and nearly so at Site B (Table 20). The retention of most of the PC N as organic N in the soil may have been due to the resistance of the PC organic N fraction to microbial attack or to immobilization during decomposition due to the high C:N ratio (Table 7).

The speed with which the N was released from the liquid sludges confirms the status of the LDS as a fast-acting N fertilizer and suggests that LAS can be considered likewise for practical purposes. The lower amount and slower rate of release of N from the PC confirms the status of this sludge as a slow release N fertilizer.

4.4 N balance

4.4.1 Results

The amount of N applied to plots receiving the C, AN3, LDS3, LAS3, and PC treatments was known (Chapter 3). The total amount of N removed in grass harvested was estimated from the N yield results. The amount of N removed in grass harvested in August and October 1978 was assumed to be equal to the 1979 + 1980 total divided by four.

The concentration of N in the soil at the end of the trial under plots receiving the five treatments is given in Table 19.

Table 19 The Effect of the C, AN3, LDS3, LAS3 and PC Treatments on the Concentration of N in the Soil at the End of the Field Trial.

Site	Soil N concentration $gN\ kg^{-1}$ dry soil					Sign.
	Treatment					
	C	PC	LDS3	LAS3	AN3	
A	1.87a	2.81bc	2.23c	2.13bc	1.97ab	***
B	4.67	5.14	4.57	4.98	4.74	NS

Treatments within a row bearing the same letter are not significantly ($p<0.05$) different.

The results were analysed by a two - way analysis of variance and the significance of the differences between individual treatment effects was determined using Tukey's W procedure. Although there were no significant ($p<0.05$) differences between the treatment effects at Site B, the results were used in the construction of the N balance for completeness. The amount of N retained in the soil was calculated from the soil analysis and the estimated weight of soil in a 7.5cm ha (Table 9).

At Site A most of the N applied to the plots was recovered in either the grass harvested or in the soil whereas at Site B the fate of much of the applied N could not be accounted for (Table20).

The proportion of the applied N which was recovered in the soil increased as the estimated availability of the N source (Table 15) decreased. An exception was the LDS at Site B as none of the applied N was recovered in the soil.

Table 20 The Fate of N Applied in the PC, LDS3, LAS3 and AN3 Treatments.

Site		N kg ha^{-1}			
		Treatment			
		PC	LDS3	LAS3	AN3
A	N applied	467	768	737	750
	N recovered in grass	67	224	294	471
	N recovered in soil	527	603	442	170
	Discrepancy	+127	+59	-1	-109
B	N applied	467	762	762	750
	N recovered in grass	52	175	213	444
	N recovered in soil	335	-71	221	50
	Discrepancy	-80	-657	-329	-260

4.4.2 Discussion

The N balance (Table 20) suggests that the main reason for the lower availability of the sludge N in comparison with the AN N was due to the retention of much of the N in the soil. It is not possible to determine from these results whether this organic N was derived from sludge organic N resistant to microbial attack or from the immobilization of mineralized sludge N or both.

Organic N derived from sludge N resistant to microbial attack or from the immobilization of N during the decomposition of sludge organic matter would be expected to have remained near the soil surface whilst organic N derived from sludge or AN N absorbed by the grass and subsequently immobilized in living and dead roots would have been expected to have been distributed down the soil profile. The decrease in the proportion of the applied N recovered in the grass and soil at Site A as the availability of the N source increased probably reflects a failure of the soil sampling method to recover N redistributed down the profile. This suggests that the recovery of N applied in all sources was nearly complete at this site ie there was no substantial loss of AN N from this site due to the winterkill (p 64). It is unlikely that a failure in the soil sampling method would have created sufficient error to account for all the discrepancies in the N balance at Site B. Experimental error may have been responsible for much of the discrepancy although the very large discrepancy in the LDS N balance may also have been due in part to a loss of N by volatilization or denitrification (p 66).

4.5 Summary and conclusions

The availability of the LDS, LAS and PC N to the grass in this trial was about 46%, 50% and 16% respectively on the sandy loam soil and about 35%, 48% and 20% respectively on the clay soil. The main reason for the less than 100% availability of the sludge N was the continued immobility of the N in the soil. The availability of the LDS N was negatively correlated with rainfall at both sites. The origin of this relationship at Site A was not determined whereas it is possible that at Site B it was due to an increasing loss of N by denitrification with increasing rainfall. The greater magnitude of the gaseous losses of N may also have been responsible for the lower availability of the LDS N on the clay soil. Further work is required to determine the magnitude and factors affecting the gaseous losses of N from surface applied LDS under UK environmental conditions.

The rate of release of N from the liquid sludges was sufficiently rapid to justify their consideration as fast-acting N fertilizers. However, the variation in the availability of the liquid sludge N is probably sufficient to reduce their value as tools for the management of grass production. The availability of the PC-N was about 16% at Site A and about 20% at Site B and the rate of release of the N was much slower than that of the liquid sludges.

An interaction between the N and H_2O in LDS of the type proposed by Coker (1978) was not found in this trial and is unlikely to be of importance on most grasslands.

CHAPTER 5

DM YIELD

The DM yield results were analysed by a two - way analysis of variance for each site/cut to obtain an estimate of the error mean square based on as large a sample as possible and to determine the coefficient of variation (not shown). The background variability of the data was greater at Site B than Site A, especially in 1979.

The results were split into its three components for further analysis and for the presentation and discussion of the results.

5.1 Component 1

5.1.1 Results

The relationship between the DM yield and N applied in AN, LDS or LAS in each cut/site and year is shown in Figs 25 to 34.

An analysis of variance of these results found a significant ($p < 0.05$) difference between the effects of the three sources of N in the annual DM yield of both years and sites and in all sites/cuts except cuts 1, 3 and 4, 1979 at Site B. The significance of the differences between individual source effects was determined using Tukey's W procedure (Table 21). This found the effect of the AN treatments to be greater than that of the LDS or LAS in most site/cuts and in three of the four site/years. In cut 1, 1979, at Site A the effect of the AN was significantly ($p < 0.05$) less than that of either sludge and in cut 1, 1980, at Site A it was significantly ($p < 0.05$) less than that of the LAS. The effect of AN and LAS treatments on the annual DM yield in 1980 at Site A was not significantly ($p < 0.05$) different although the effect of the AN was significantly ($p < 0.05$) greater than that of the LDS. The effects of the sludge were only significantly ($p < 0.05$) different in cut 1, 1979, at Site A.

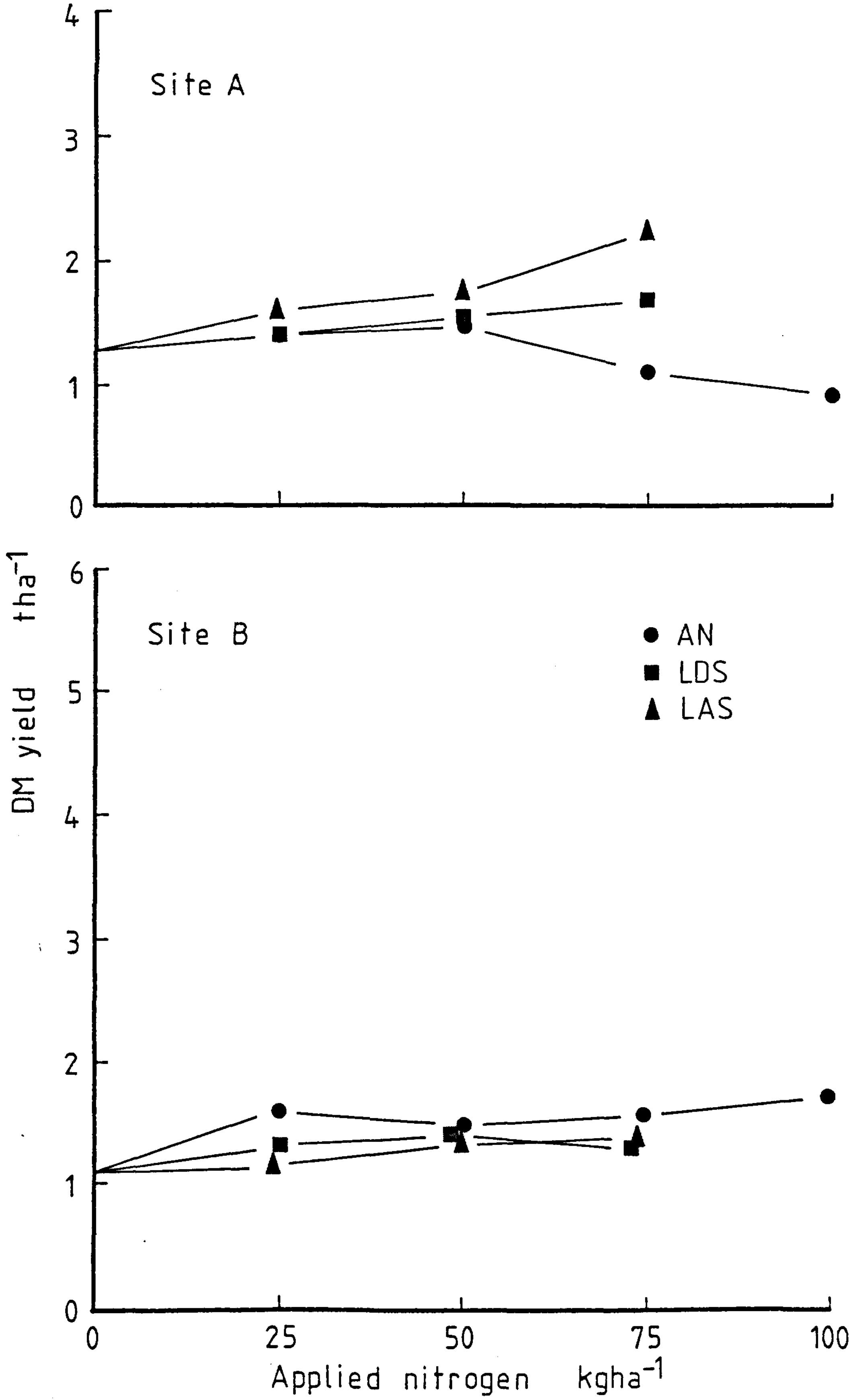


Fig 25 The relationship between DM yield and applied nitrogen in cut 1, 1979.

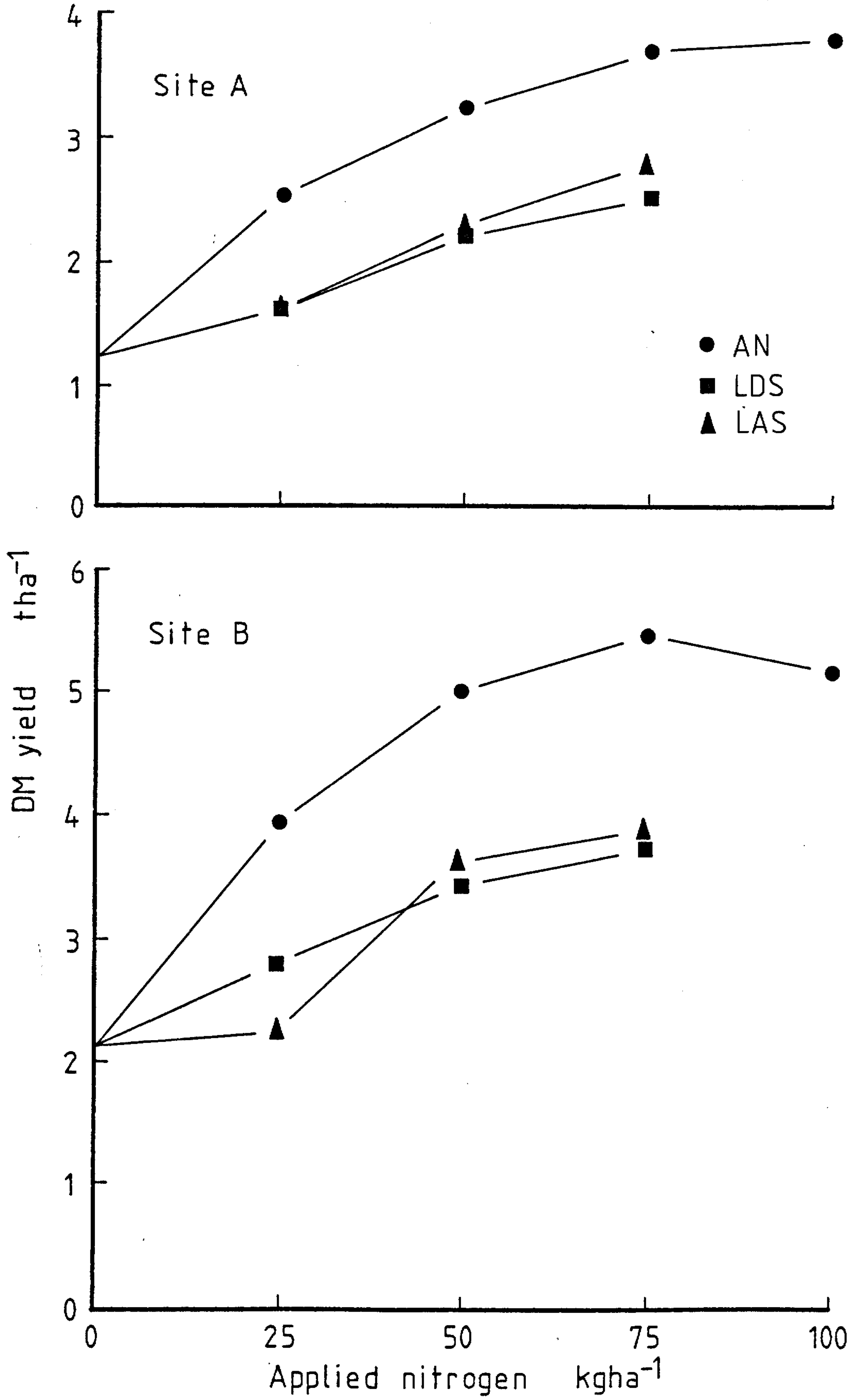


Fig 26 The relationship between DM yield and applied nitrogen in cut 2, 1979.

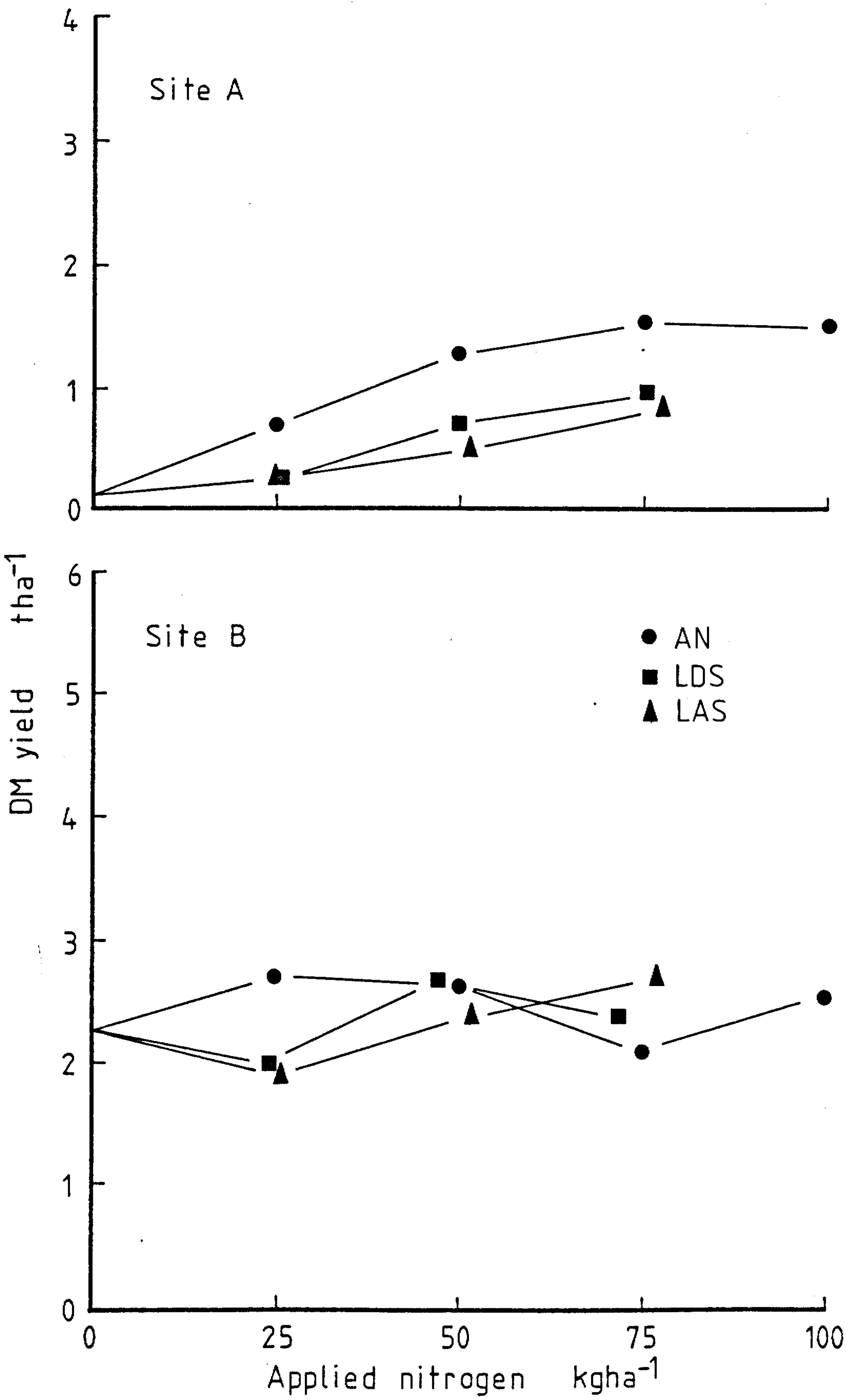


Fig 27 The relationship between DM yield and applied nitrogen in cut 3, 1979.

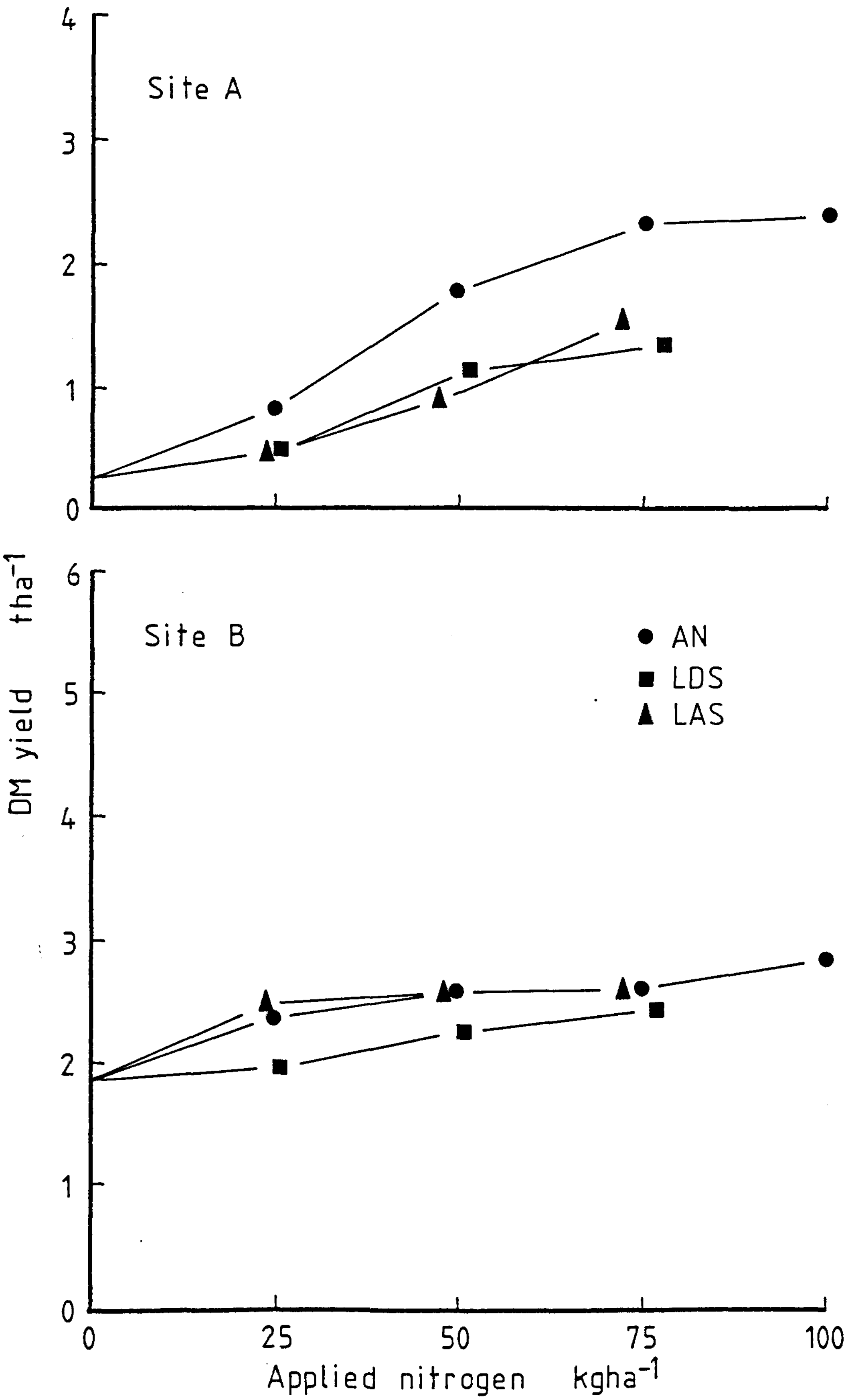


Fig 28 The relationship between DM yield and applied nitrogen in cut 4, 1979.

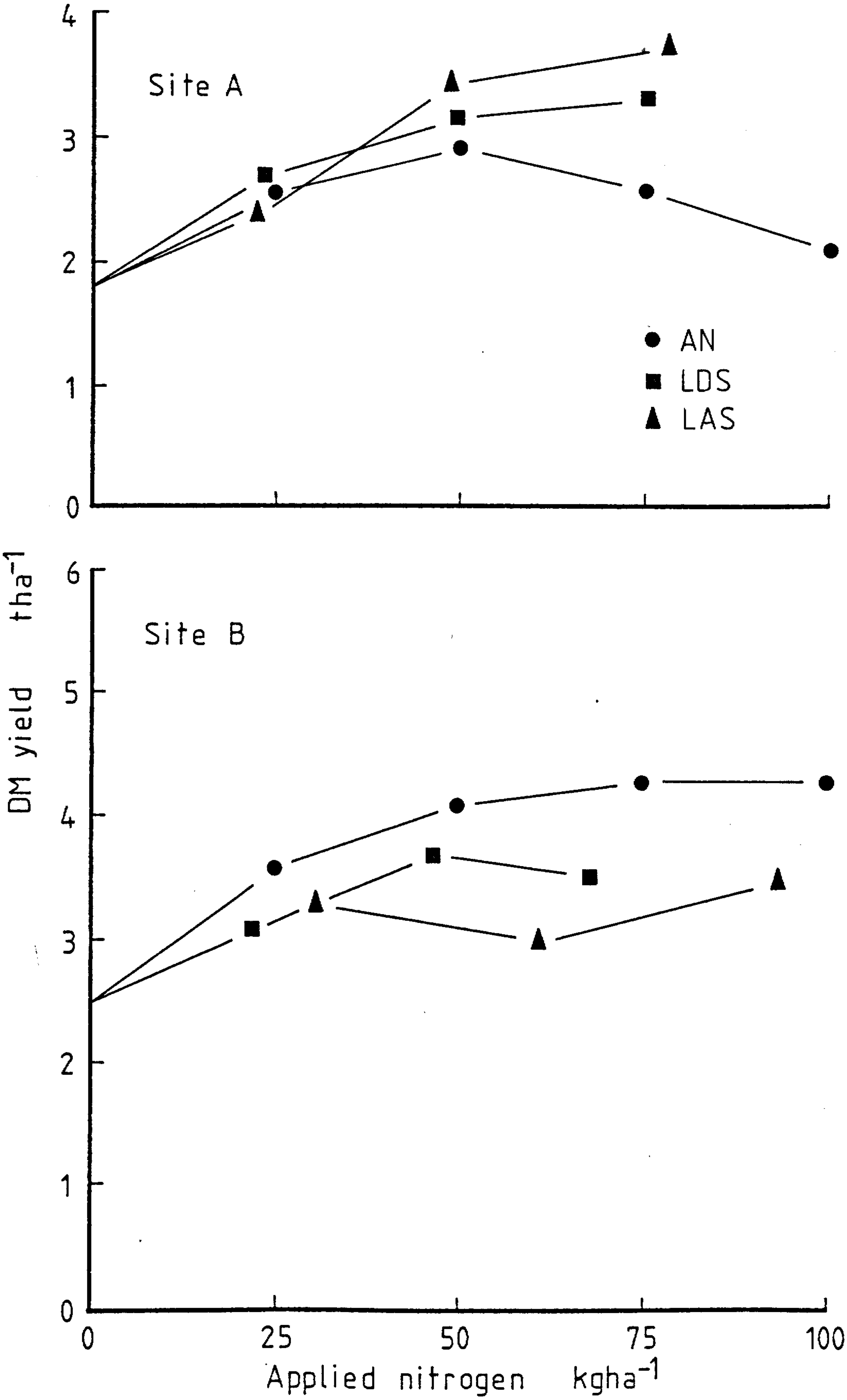


Fig 29 The relationship between DM yield and applied nitrogen in cut 1, 1980.

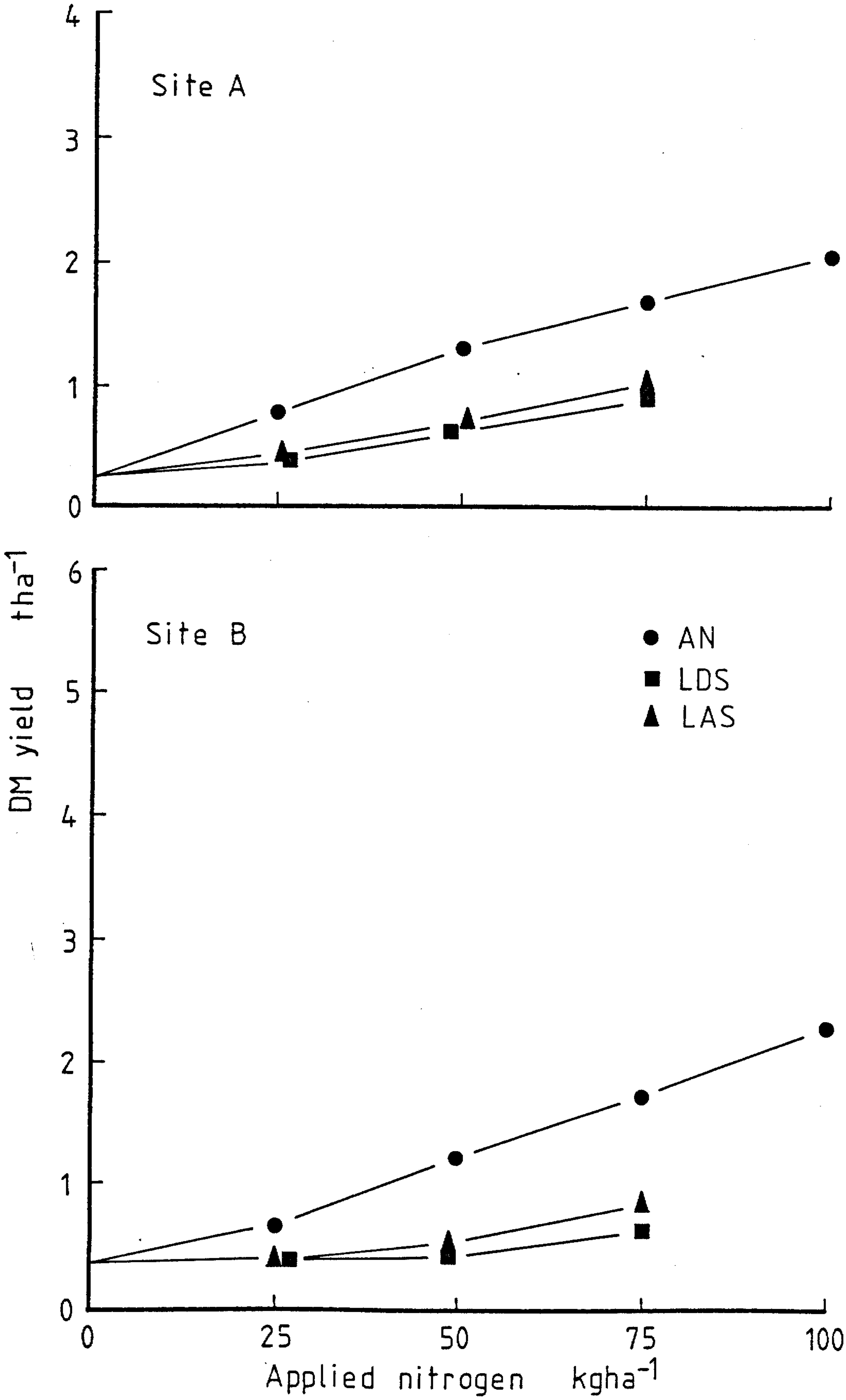


Fig 30 The relationship between DM yield and applied nitrogen in cut 2, 1980.

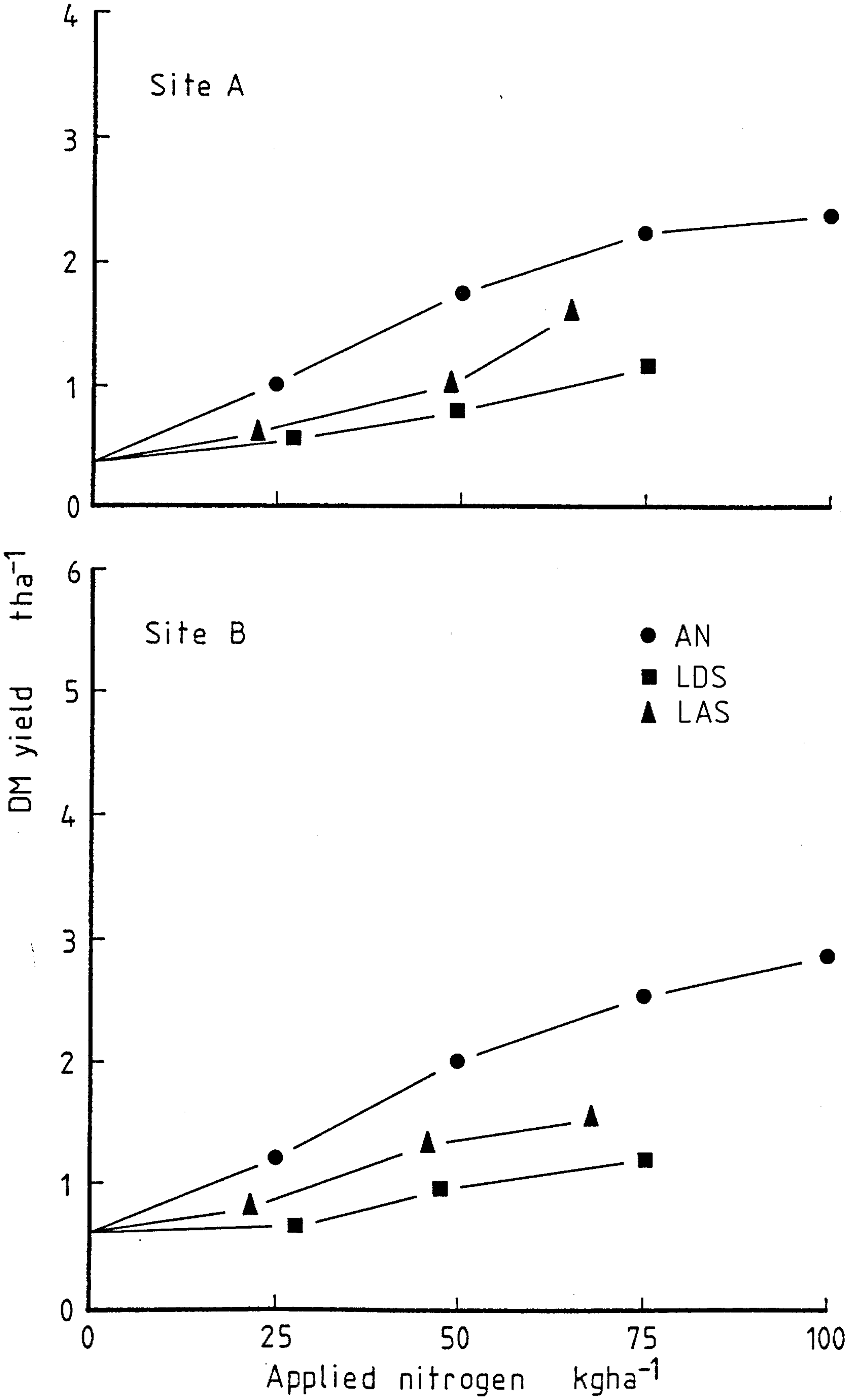


Fig 31 The relationship between DM yield and applied nitrogen in cut 3, 1980.

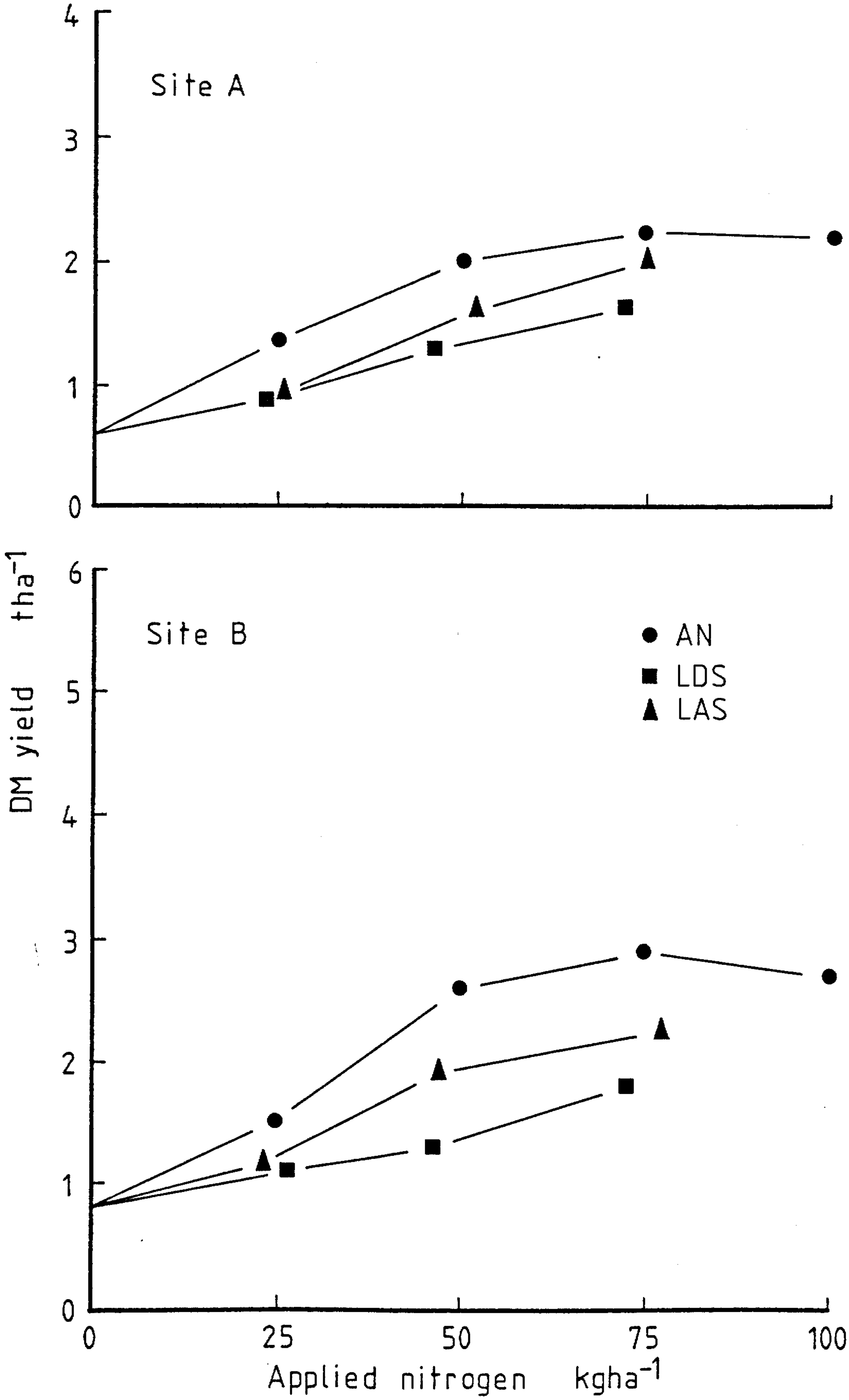


Fig 32 The relationship between DM yield and applied nitrogen in cut 4, 1980.

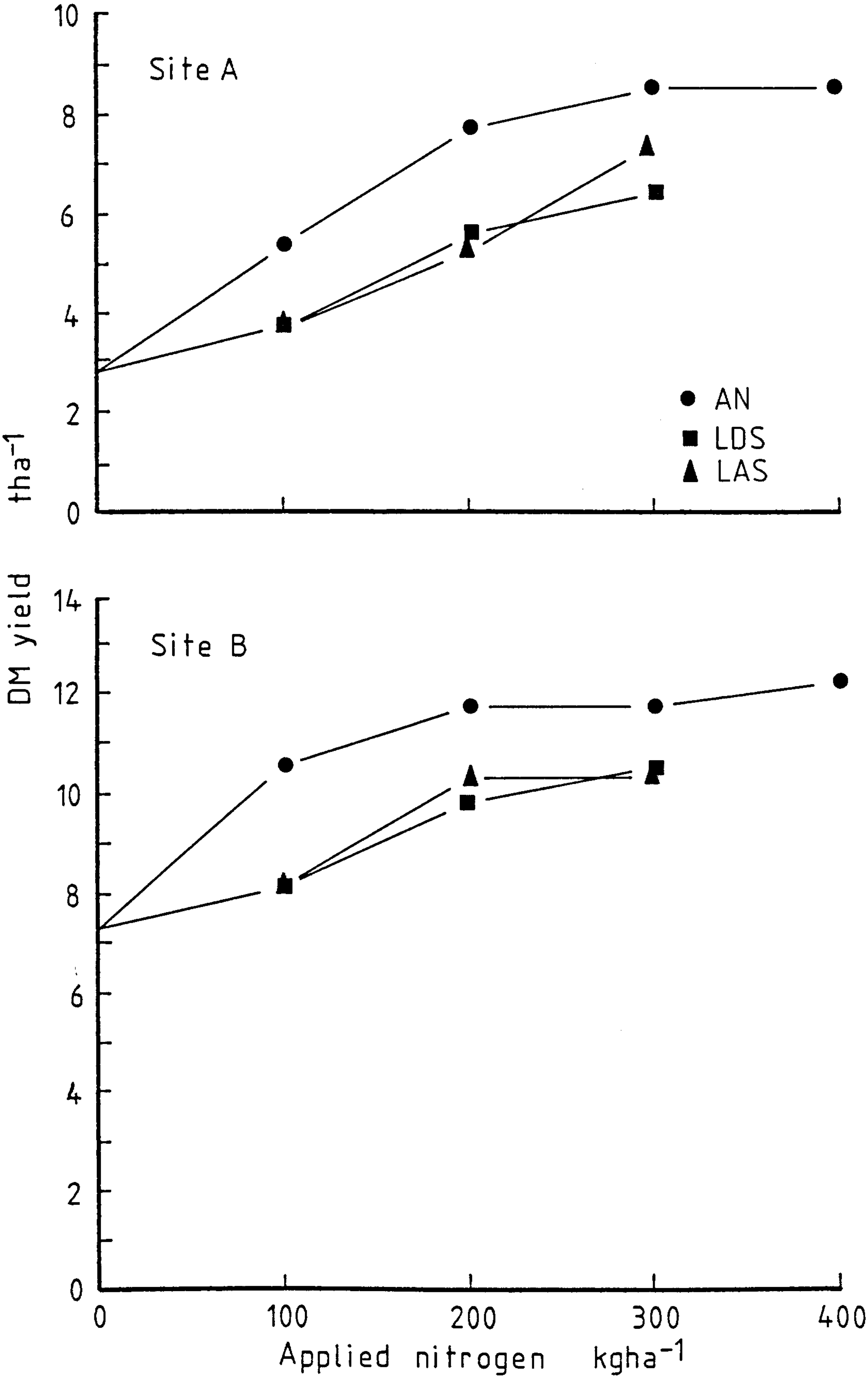


Fig 33 The relationship between the annual DM yield and applied nitrogen in 1979.

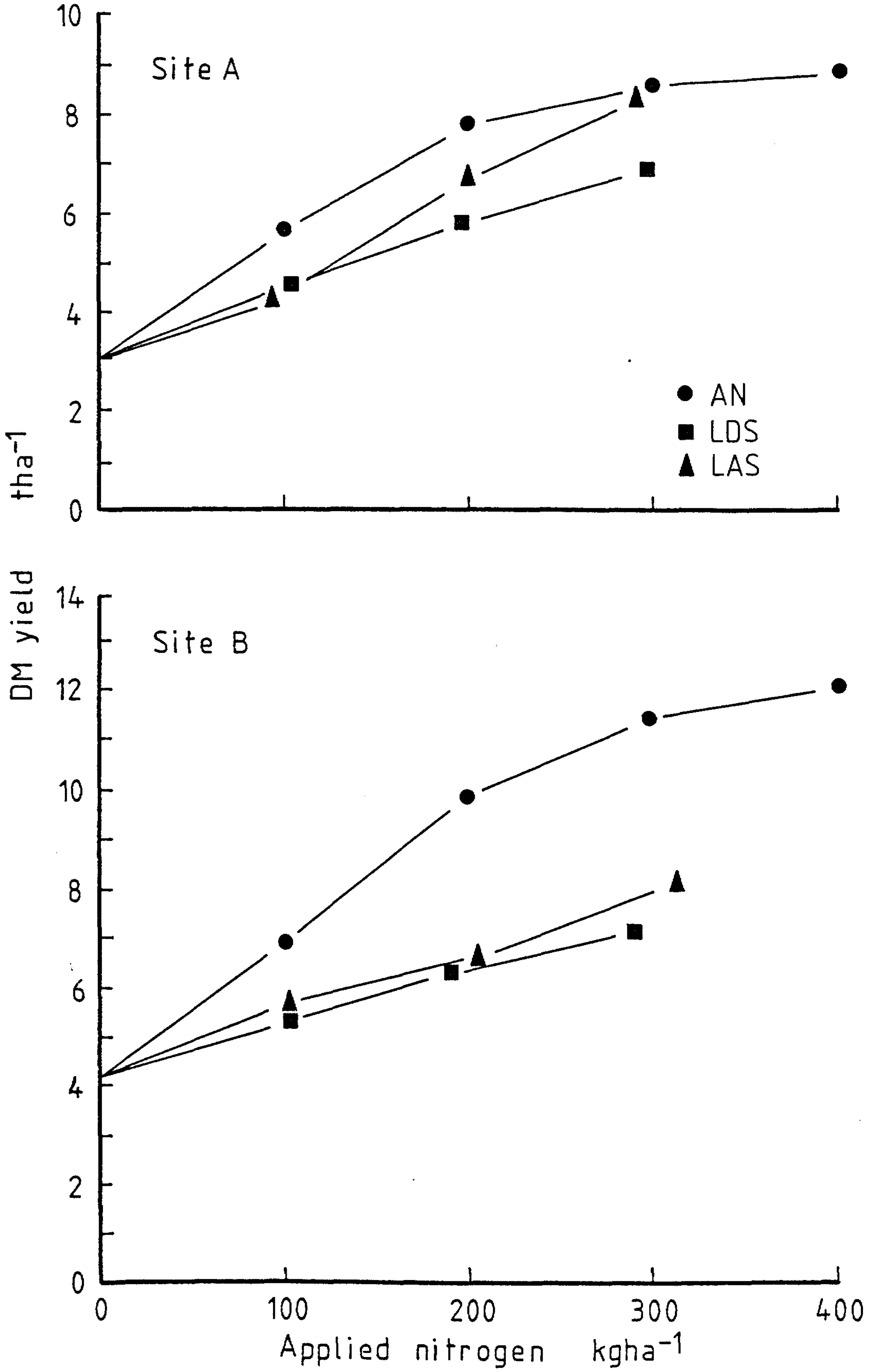


Fig 34 The relationship between the annual DM yield and applied nitrogen in 1980.

Table 21 The Significance of the Differences between the Effects of Sources of N on DM Yield

		Site A			Site B		
	Cut	Increasing DM Yield →					
1979	1	AN	LDS	LAS		NS	
	2	LDS	LAS	AN	LAS	LDS	AN
	3	LAS	LDS	AN		NS	
	4	LAS	LDS	AN		NS	
Total		LDS	LAS	AN	LDS	LAS	AN
1980	1	AN	LDS	LAS	LAS	LDS	AN
	2	LDS	LAS	AN	LDS	LAS	AN
	3	LDS	LAS	AN	LDS	LAS	AN
	4	LDS	LAS	AN	LDS	LAS	AN
Total		LDS	LAS	AN	LDS	LAS	AN

Source effects not underlined by a common line are significantly different ($p < 0.05$) as determined by Tukey's W procedure.

NS Source effect not significantly ($p > 0.05$) different by analysis of variance.

A response analysis found a significant ($p < 0.05$) positive response to the applications of AN in all site/years and in all site/cuts except cut 3, 1979, at Site B (Table 22). The response in most site/cuts contained both significant ($p < 0.05$) linear and quadratic components. The quadratic component was associated with a reduction in the response to AN at high application levels. There was a significant ($p < 0.05$) response to the application of LDS N in all site/years and in all site/cuts except cut 1, 3 and 4, 1979 and cut 2, 1980, at Site B. There was a significant ($p < 0.05$) response to the application of LAS N in all site/years and in all site/cuts except cut 1 and 3, 1979, at Site B. The response to the sludges was predominantly linear although non-linear components were present occasionally. These were usually associated with an increase in the rate of response with increasing level of application when the DM yield of the control plots was low. Exceptions were the non-linear components in the response to LAS N in cut 2, 1979, and cut 1, 1980, at Site B (Figs 26 and 29).

5.1.2 Discussion

The response of the DM yield to applications of the three N sources was similar to that of the N yield (Figs 10 to 15). The reduction in marginal response (kg DM kg^{-1} N applied) with increasing level of application of AN was more apparent in the DM yield response than was the equivalent reduction in the response of N yield. This was true for both the reduction in response as the DM yield approached the maximum yield potential (eg in cut 2, 1979, at Site A and B) and the reduction due to the winterkill of grass at Site A (cut 1, 1979 and 1980). This reduction in the DM response to applied N with increasing level of

Table 22 The Analysis of the response of DM yield to Applications of AN, LDS and LAS

Source	Component	Cut No 1		Cut No 2		Cut No 3		Cut No 4		Total	
		Site A	Site B	Site A	Site B	Site A	Site B	Site A	Site B	Site A	Site B
						1979					
AN	LIN	**	*	***	***	***	NS	***	**	***	***
	QUAD	*	NS	***	***	***	NS	***	NS	***	***
	CUBIC	NS	NS	NS	NS	*	NS	***	NS	NS	NS
	RESID	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	*	NS	***	***	***	NS	***	NS	***	***
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	*	NS	**	NS	*	NS
LAS	LIN	***	NS	***	***	***	NS	***	*	***	***
	QUAD	NS	NS	NS	NS	*	NS	**	NS	*	NS
	RESID	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
						1980					
AN	LIN	NS	***	***	***	***	***	***	***	***	***
	QUAD	***	***	NS	NS	NS	NS	***	***	**	*
	CUBIC	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	***	***	***	NS	***	***	***	***	***	***
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	***	*	***	**	***	***	***	***	***	***
	QUAD	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
	RESID	NS	*	NS	NS	NS	NS	NS	NS	NS	NS

application suggests that estimates of the availability of sludge N must be based upon the comparison of the amount of AN and sludge N required to obtain the same DM yield if N analyses are not available.

The non-linear components in the DM response to applications of the sludges which occurred when the DM yield from control plots was low are probably due to the retention of much of the sludge N in the soil and stubble (p 64). The non-linear components in the DM response to LAS in cut 2, 1979, and cut 1, 1980, cannot be interpreted as a reduction in the response due to the DM yield approaching the maximum yield potential or a poor response due to the retention of N in the soil and stubble. The origin of these components (if real effects) remains unknown.

The marginal response to the N sources varied considerably over the season (compare cut 1 and 2, 1979, at Site B) due to environmental and physiological factors. This suggests that estimations of the availability of sludge N based upon the annual DM yield response to several sludge applications are likely to be biased in favour of the sludges applied in the spring when the response to N is large.

To determine whether the efficiency with which absorbed N was used to create DM (E_N) differed between N sources, the DM yield results were plotted against the N yield results (Figs 35 and 36). Only results from sites in which there was a significant ($p < 0.05$) response to N were plotted.

The relationship between DM and N yield for the three N sources appeared to be coincident in all of the site/cuts except cut 1 in both years at Site A. This indicates that the difference in the DM response to the three sources could be adequately explained by the differences in the availability of the N. The apparent discrepancy in the first cut of each year at Site A was probably due to the winterkill

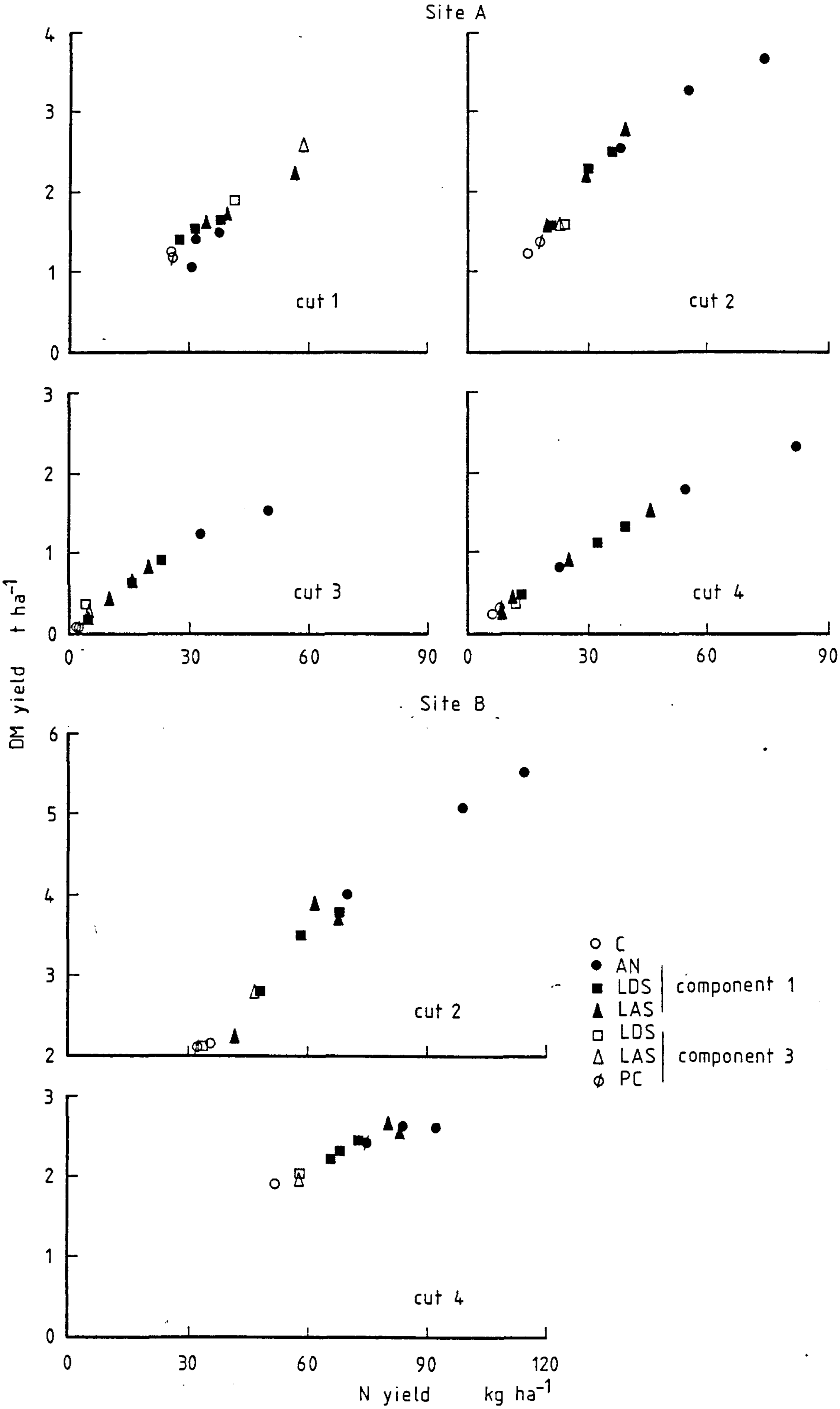


Fig 35 The relationship between DM yield and N yield in 1979.

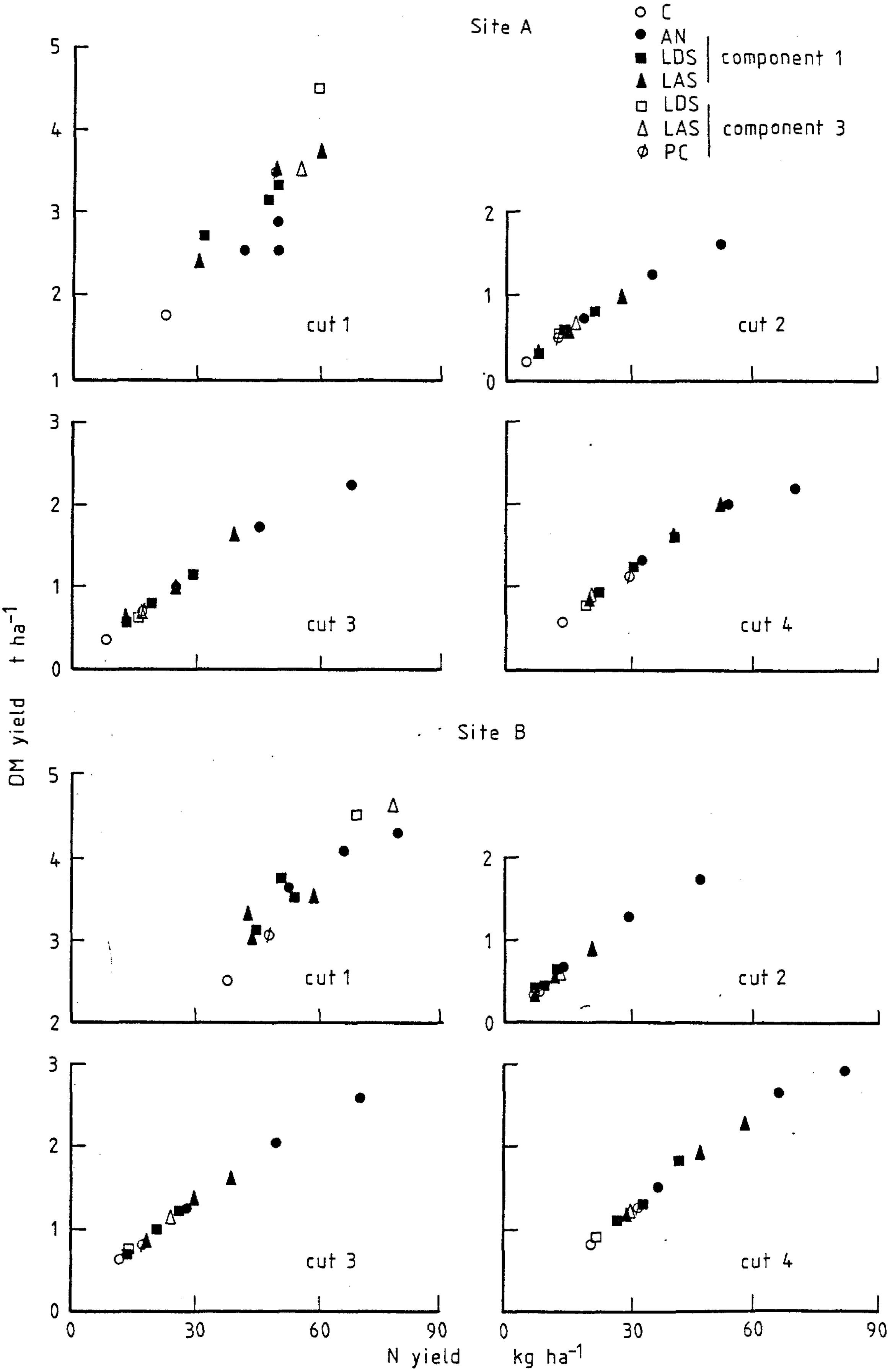


Fig 36 The relationship between DM yield and N yield in 1980

of the sward receiving AN leading to a reduction in the ability of the grass to fully utilize the applied N.

The absence of any difference between the E_N of N from different sources is surprising as N from an organic N source such as LAS would not be expected to have been used as effectively to produce DM as that from AN (p 24).

The practical implication of the similarity in E_N between sources is that available sludge N can be used to replace AN with the expectation of obtaining the same DM yield.

5.2 Component 2

5.2.1 Results

The DM yield of grass removed in each cut from plots receiving the W and W + AN2 treatments is given in Table 23.

The application of the W treatment did not significantly ($p < 0.05$) increase or decrease the DM yield in comparison with that removed from the C plots. The W + AN2 significantly ($p < 0.01$) decreased the DM yield in comparison with the AN2 treatment in cut 4, 1979, at Site A. There was no significant ($p < 0.05$) difference between the E_N of N absorbed from the W and W + AN2 treatments in comparison with the same treatment without H_2O (results not shown).

The effects of the C and AN2 treatments are included for comparison.

5.2.2 Discussion

As the applications of H_2O had no significant ($p < 0.05$) effect on E_N, the differences between the DM yield from plots receiving the W and W + AN2 treatment and those receiving the C and AN2 treatment reflect the differences in the amount of N absorbed (Fig 22 and 23).

The effects of the application of H_2O on N and DM yield were small in comparison with the total response to N. The amount of inorganic N

Table 23 The Effect of Component 2 Treatments on DM Yield and the Comparison with the Equivalent Treatments without Water

Treatments and Significance of Difference	DM Yield t ha^{-1}									
	Cut No								Total	
	1		2		3		4			
	Site									
	A	B	A	B	A	B	A	B	A	B
	1979									
W	1.29	1.39	1.26	1.59	0.09	1.95	0.25	2.14	2.89	7.07
C	1.25	1.10	1.24	2.16	0.14	2.28	0.24	1.90	2.86	7.44
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W + IN2	1.58	1.44	3.59	5.44	1.19	2.51	1.50	2.72	7.87	12.10
IN2	1.45	1.53	3.27	5.07	1.26	2.65	1.79	2.65	7.76	11.92
Significance	NS	NS	NS	NS	NS	NS	**	NS	NS	NS
	1980									
W	2.01	2.52	0.28	0.27	0.35	0.41	0.64	0.87	3.28	4.07
C	1.79	2.48	0.24	0.38	0.35	0.63	0.59	0.82	2.98	4.30
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W + IN2	3.28	4.04	1.26	1.27	1.93	2.11	2.23	2.70	8.69	10.11
IN2	2.89	4.06	1.30	1.26	1.71	2.01	1.99	2.62	7.89	9.95
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

applied in the LDS2 treatment averaged one third that applied in the W + AN2 treatment. It is therefore very unlikely that H_2O x N interactions of the type proposed by Coker (1979) were important in determining the action of the LDS N. These interactions may be of greater importance when the LDS applied contains a greater proportion of NH_4^+- N or when larger amounts of H_2O are applied. However, as the H_2O x N interactions were nearly counteractive then unless additional H_2O reduces the loss of NH_4^+- N by volatilization the water will act to redistribute N absorption and DM yield over the season with little net effect on the annual N or DM yield.

5.3 Component 3

5.3.1 Results

The seasonal distribution of the DM yield increases due to the application of Component 3 treatments is shown in Fig 37 and 38. The annual increases in DM yield are shown in Table 24.

The DM yield responses to Component 3 treatments were greater in 1980 than in 1979 at both sites and tended to be greater at Site A than at Site B in both years. The proportions of the total DM yield increase which was recovered in the first cut increased in the order PC < LAS < LDS.

Table 24 Increases in DM Yield due to Component 3 Treatments

	Sludge					
	LDS		LAS		PC	
	Site					
	A	B	A	B	A	B
	1979					
Increase in DM Yield t ha^{-1}	1.31	0.48	1.93	1.35	0.14	0.91
Marginal Response kg DM kg^{-1}N	8.7	3.3	12.9	8.3	1.5	9.9
Significance	**	NS	**	NS	NS	NS
	1980					
Increase in DM Yield t ha^{-1}	3.44	2.16	2.82	3.25	2.85	1.26
Marginal Response kg DM kg^{-1} N	23.1	16.6	19.3	17.5	7.8	3.5
Significance	**	**	**	**	**	*

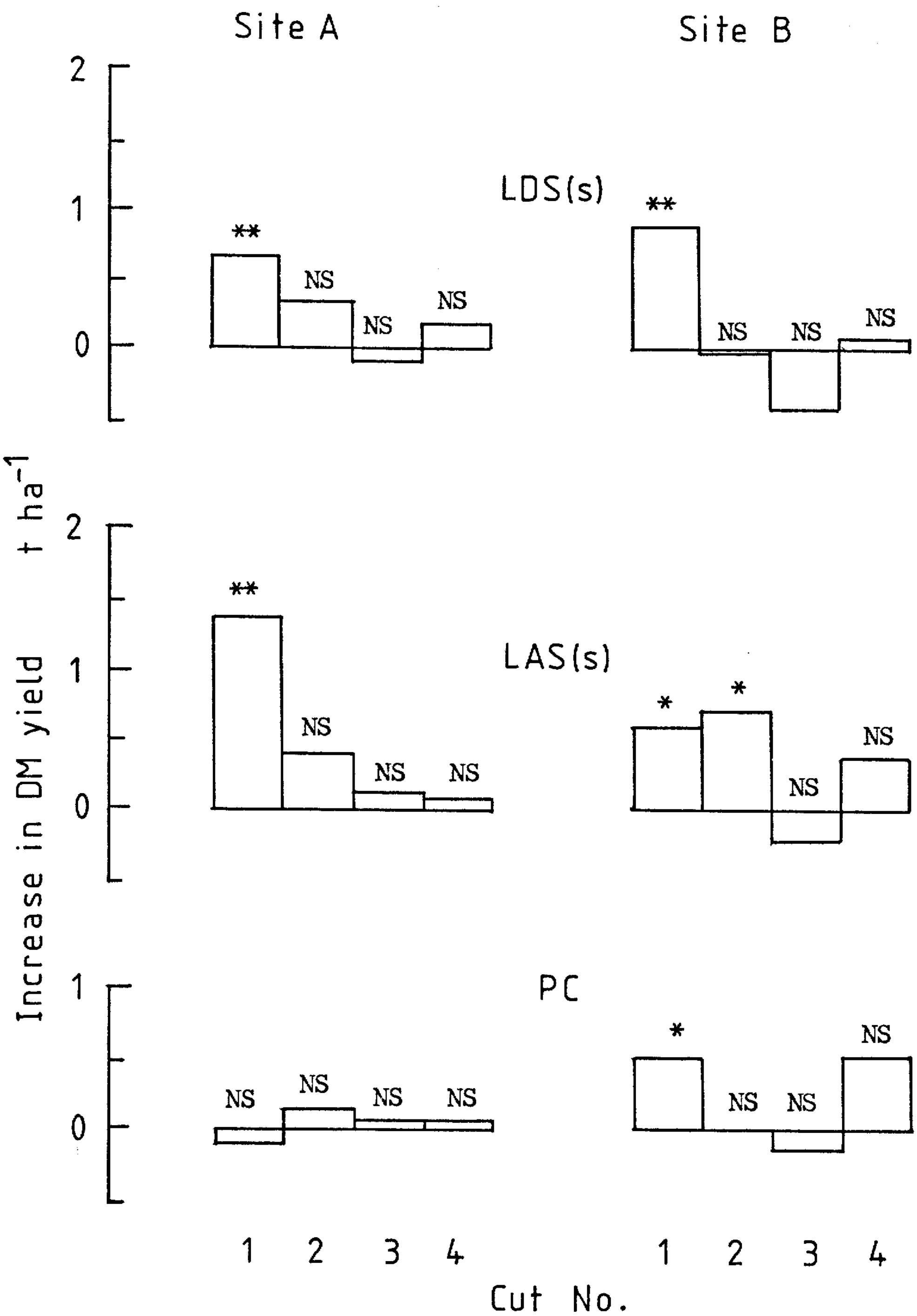


Fig 37 The increase in DM yield due to the application of the Component 3 treatments in 1979.

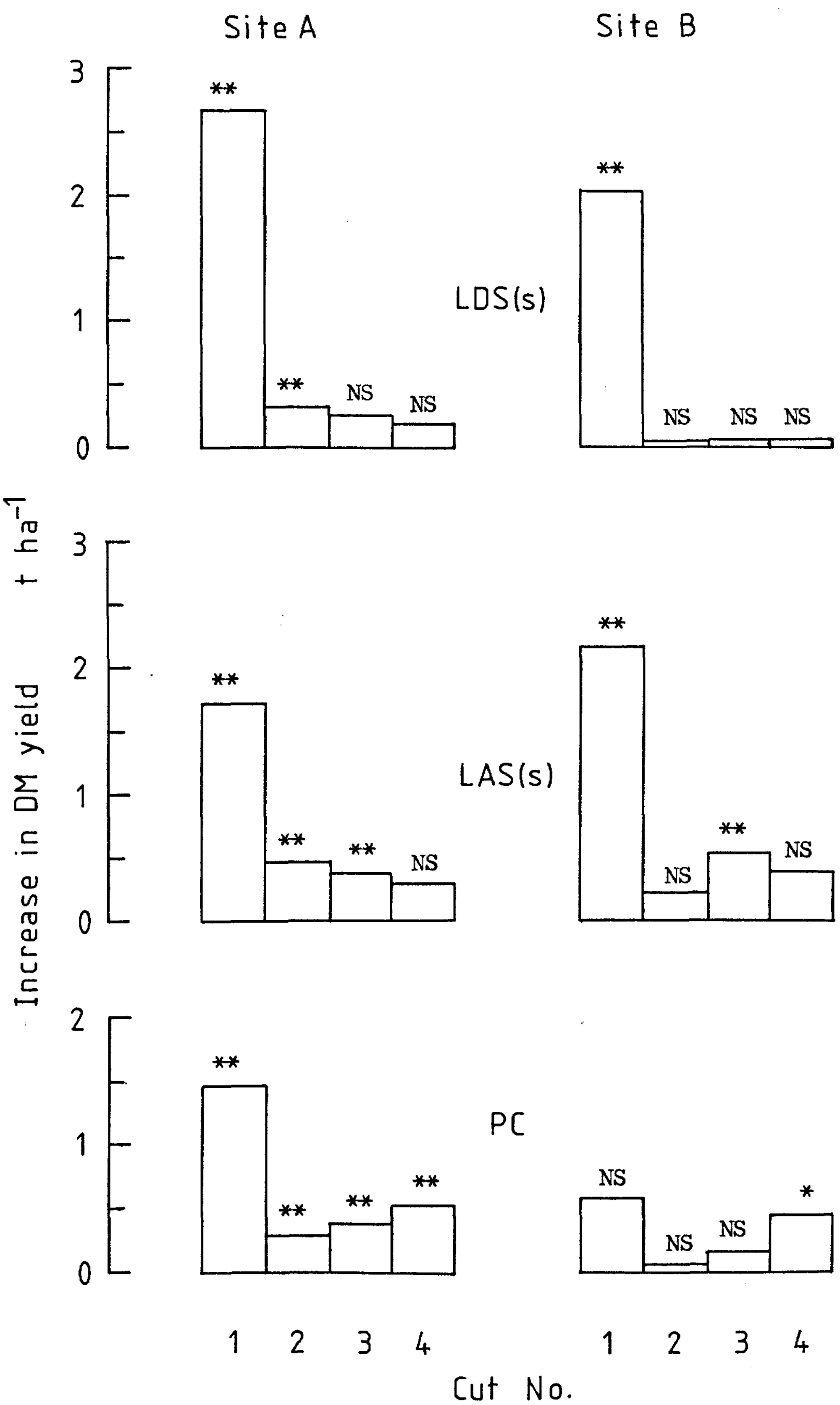


Fig 38 The increase in DM yield due to the application of the Component 3 treatments in 1980.

5.3.2 Discussion

The poor responses to Component 3 treatments in 1979 were probably due to the cool, wet weather which prevailed in the first growth period. The response to the PC treatment was increased in 1980 by the application of nearly four times as much N as applied for 1979. The reasons for the lower response to sludge N at Site B than at Site B have been discussed earlier (p 66).

The pattern of DM yield increases followed that of the release of N from the sludges (Fig 22 and 23) although the relationship between the treatment effects on DM and N yields in individual cuts varied due to seasonal changes in E_N. The E_N of N absorbed from the Component 3 treatments was similar to that of the Component 1 treatments within each cut (Fig 35 to 36). It is surprising that the N absorbed from a slow release source such as PC or the residual LDS and LAS N should have been used as effectively to create DM as N supplied in AN (p 24).

The marginal responses to LDS and LAS N applied in Component 3 treatments can be compared with that which might have been obtained had the same amount of N been applied in 4 equally split applications over the season (Table 25). The difference between the average effect of the two applications strategies was small but concealed major differences between the results in the two years. In 1979 the Component 1 strategy produced a greater DM yield response than the Component 3 strategy as the DM response to N in the spring of this year was depressed by bad weather. In 1980 the position was reversed despite a very dry period during the first growth period. This suggests that in most years the Component 3 strategy will produce a greater DM yield response than the Component 1 strategy due to the high spring E_N, but that the response to the Component 1 strategy will be less affected by variations in the spring weather between years.

Table 25 The Marginal Response to LDS and LAS N applied in Component 1 and Component 3 of the Field Trial

Year	Site	Marginal Response kg DM kg^{-1} N			
		Sludge			
		LDS		LAS	
		Component			
		1	3	1	3
1979	A	12.4	8.7	14.9	12.4
	B	10.2	3.3	11.2	8.3
1980	A	13.4	23.1	18.7	19.3
	B	10.1	16.6	12.3	17.5
Mean		11.5	12.9	14.3	14.5

5.4 Summary and conclusions

Except when the ability of the sward to respond to N had been impaired by winterkill, the efficiency with which N absorbed by the grass was used to create DM was the same, irrespective of the source of that N. However, the DM yield response to treatments supplying the same amount of total N but different amounts of available N did not reflect these differences due to the reduction in E_N which occurs as N supply is increased. Studies in which the availability of sludge N is based upon the response of annual DM yield to several applications of sludge are unlikely to give a balanced estimate as the result is likely to be weighted in favour of the availability of sludge(s) applied early in the growth season.

There was little effect of the application of H_2O on E_N so the differences in DM yield between treatments with and without H_2O reflected differences in the supply of N to the grass. The activity of the sludge H_2O is unlikely to be of agricultural importance unless the rate of application is high.

In 1979 the annual DM yield response to the liquid sludges applied in four equal amounts was greater than the response to the same amount of the sludges applied in one application in the spring. In 1980 the positions were reversed. It is likely that in most years the DM yield response to a single spring application would be greater than to split applications provided the supply of available N was not excessive. However, this advantage is obtained at the risk of occasional shortfalls in yield due to bad spring weather.

CHAPTER 6

GRASS QUALITY

The objectives of the examination of the effect of sludge applications on the quality of the grass were to determine:-

1) Whether any such effects existed and their consequences.

2) If the relationship between the effects of the AN, LDS and LAS on grass quality could be accounted for by the difference in N availability between the sources.

3) If a single, large application of sludge applied for a spring silage cut would have a similar effect and whether the grass would be suitable for ensiling.

Point 1 and 2 were investigated by an examination of the effects of a selection of the Component 1 treatments whilst point 3 was investigated by an examination of the effects of Component 3 treatments in cut 1.

6.1 Component 1 treatment effects

6.1.1 Crude protein

6.1.1.1 Results

The concentration of CP in the grass harvested from plots receiving the Component 1 treatments is given in Table 26 and 27.

A response analysis found a significant ($p < 0.05$) positive response to the application of AN in all site/cuts, to the application of LDS in all site/cuts except cuts 2, 3 and 4, 1979, and cut 1, 1980, at Site B and to the application of LAS in all site/cuts at site A, but only in cuts 2 and 3, 1980, at Site B (Table 28). The response to the application of the sludges was predominantly linear although there was a significant ($p < 0.05$) non-linear component in the response to the application of LDS in cut 1, 1980, at Site A. The linear component in the response to the application of AN was significant ($p < 0.001$) in all site/cuts but significant ($p < 0.05$) non-linear components were often present, particularly at Site A. The non-linear components were associated with an increase in the rate of response of the CP concentration with increasing application rate of AN.

The concentration of CP in grass harvested from plots receiving the level 3 application fell below 12% in one site/cut when AN was the N source but in five site/cuts when LDS or LAS was the N source.

Table 26 The Concentration of CP in the Grass in 1979

Treatment	CP % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	12.3	8.5	7.7	10.2	11.1	17.7	15.9	17.2
AN1	14.6	10.3	9.4	10.9	14.3	18.3	18.1	19.3
AN2	16.0	13.1	10.4	12.2	16.6	20.3	18.9	19.8
AN3	19.0	15.7	12.4	12.9	20.1	21.9	22.2	22.0
AN4	19.5	16.6	16.3	15.9	23.5	23.8	26.2	22.2
LDS1	12.4	9.2	8.1	10.4	12.8	18.3	17.0	17.9
LDS2	13.4	10.1	8.3	10.4	14.4	17.8	17.8	18.1
LDS3	14.1	10.6	9.1	11.2	15.6	19.3	18.7	19.1
LAS1	12.4	7.9	8.1	11.3	12.6	16.4	16.9	19.3
LAS2	14.0	10.6	8.6	11.4	13.1	18.3	18.1	18.5
LAS3	15.5	10.3	8.7	9.8	15.3	18.9	18.9	18.7

Table 27 The Concentration of CP in the Grass in 1980

Treatment	CP % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	7.7	9.3	12.1	11.1	13.9	12.1	15.0	15.8
AN1	9.9	9.0	15.5	12.3	15.8	14.2	15.1	15.3
AN2	10.6	10.0	17.0	14.9	16.5	15.4	17.1	15.8
AN3	12.4	11.6	19.5	17.1	18.8	17.3	19.8	17.4
AN4	15.3	13.3	21.1	19.9	20.8	18.6	21.2	21.6
LDS1	7.2	8.7	13.3	11.1	14.4	13.2	15.2	15.0
LDS2	9.3	8.5	14.3	12.8	15.2	13.8	15.4	15.4
LDS3	9.3	9.5	14.8	13.1	16.0	13.8	16.1	14.2
LAS1	8.1	7.9	13.4	12.3	14.5	13.3	15.3	15.3
LAS2	8.8	9.1	15.4	13.0	16.0	14.3	15.9	15.3
LAS3	10.0	10.3	16.6	14.1	15.6	15.3	16.1	15.6

6.1.1.2 Discussion

The effect of an application of a N source on the concentration of CP (6.25 x %N) in the crop depends upon the amount of extra N translocated to the aerial parts (N yield response) and to what extent this is diluted by increases in growth (DM yield response). Consequently the CP concentration = 6.25 x $^{1}/E_{N}$. As E_N decreases with increasing rate of application of N (Morrison et al., 1980) the application of the N sources tended to increase the CP concentration. The marked increases in the CP concentration in the grass cuts from plots receiving the high rates of AN which were observed in several site/cuts (eg cut 4,

Table 28 The Analysis of the Response of the Concentration of CP in the Grass to Applications of AN, LDS and LAS

N Source	Component	Cut No 1		2		3		4	
		Site A	B	A	B	A	B	A	B
		1979							
AN	LIN	***	***	***	***	***	***	***	***
	QUAD	NS	NS	***	NS	NS	NS	**	NS
	CUBIC	NS	NS	*	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	**	NS
LDS	LIN	**	**	***	NS	***	NS	***	NS
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	***	NS	*	NS	***	NS	***	NS
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
		1980							
AN	LIN	***	***	***	***	***	***	***	***
	QUAD	NS	*	NS	NS	NS	NS	**	***
	CUBIC	NS	NS	NS	NS	NS	NS	***	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	**	NS	***	***	***	**	**	*
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	*	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	**	NS	***	***	***	***	**	NS
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS

1979, at Site A and cut 4, 1980, at Site B, Table 26 and 27 were probably due to the small or absent rate of DM yield response at these levels.

As the CP concentration and E_N are related (see above), the plot of DM yield on N yield (Fig 35 and 36) can be used to determine whether the effect of the sludge application on the CP concentration can be solely accounted for by the supply of available N. The relationship between DM and N yield derived from the AN, LDS and LAS treated plots appeared coincident in all site/cuts examined except cut 1 in both years at Site A. The selective winterkill which occurred at this site (p 64) reduced the ability of the sward to utilize the applied AN and as a result, the response of the CP concentration was increased.

The similarity in the CP concentration in grass receiving LDS and inorganic N found by Coker (1966b) has not been repeated in the results of this field trial. This can be adequately explained by the difference in the amount of N present as NH_4^+- N in the sludge used by Coker (70% NH_4^+- N) and that used in this field trial (30% NH_4^+- N).

The lower availability of the sludge N in comparison with that in AN means that farmers using sludge must expect a lower protein concentration in the grass than in grass receiving the inorganic N fertilizer. In the mid and late season the supply of soil N and the lower E_N is often sufficient to ensure that the CP level in the grass is adequate for good livestock nutrition. Grass cut in the early part of the growth season may not contain the 12% CP minimum recommended for milking cow diets (Osbourne, 1980) and the response to applications of sludge may be insufficient to elevate it above this level. Consequently, supplementary feeding with a high protein source may be required.

6.1.2 Modified acid detergent fibre

6.1.2.1 Results

The concentration of MADF in the grass harvested from plots receiving the Component 1 treatments is given in Table 29 and 30.

Table 29 The Concentration of MADF in the Grass in 1979

Treatment	MADF % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	25.4	22.8	29.3	32.1	28.3	25.9	24.2	24.5
AN1	26.0	23.9	28.2	32.5	23.9	25.2	23.3	24.1
AN2	26.2	24.8	29.8	33.6	23.3	25.6	23.8	24.2
AN3	25.4	25.1	30.4	31.5	22.2	23.7	24.9	23.0
LDS1	26.0	23.0	28.3	31.0	25.6	25.7	23.9	25.2
LDS2	25.8	23.3	29.6	29.2	24.9	24.8	24.0	24.3
LDS3	26.2	24.2	28.4	33.2	24.7	25.4	23.9	25.1
LAS1	25.0	23.3	27.4	31.8	26.7	24.6	23.5	29.4
LAS2	25.8	23.6	28.3	24.5	25.9	25.4	23.6	24.6
LAS3	28.1	23.3	27.5	30.7	23.7	25.9	24.0	25.8

Table 30 The Concentration of MADF in the Grass in 1980

Treatment	MADF % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	28.7	31.0	26.6	27.9	29.1	28.7	26.0	26.3
AN1	29.1	30.7	23.8	25.0	29.5	28.6	27.1	25.5
AN2	29.3	31.1	24.3	24.4	29.2	30.0	25.4	25.6
AN3	28.7	31.3	23.2	24.3	28.8	30.0	25.1	25.8
LDS1	29.2	30.2	24.9	26.7	27.7	27.8	25.9	25.9
LDS2	30.0	31.1	25.3	25.2	29.5	28.6	26.7	25.7
LDS3	29.8	30.6	24.2	25.0	28.3	29.4	26.7	26.4
LAS1	29.2	31.0	24.5	26.1	28.9	28.2	25.9	26.7
LAS2	29.8	30.9	23.7	24.8	29.6	29.0	27.0	26.2
LAS3	30.3	31.0	24.2	24.8	29.9	29.8	26.7	26.7

A response analysis found a significant ($p < 0.05$) positive response to the applications of AN in cut 3, 1979, and cut 2 and 4, 1980, at Site A and in cut 3 and 4, 1979, and cut 2, 1980, at Site B, but a significant ($p < 0.05$) positive response in cut 1, 1979, at Site B (Table 31). There was a significant ($p < 0.05$) negative response to the application of LDS in cut 3, 1979, and cut 2, 1980, at Site A and in cut 2, 1980, at Site B, but a significant ($p < 0.05$) positive response in cut 1, 1980, at Site A. There was a significant ($p < 0.05$) negative response to the applications of LAS in cut 3, 1979, at Site A and cut 2, 1980, at both sites, a significant ($p < 0.05$) positive response in cut 1 in both years at Site A and a significant ($p < 0.05$) positive and negative response in cut 3, 1979, at Site B. There were significant ($p < 0.05$) non-linear components in the response to the application of one or more of the N sources in cut 3, 1979, and cut 2, 1980, at both sites and in cut 4, 1980, at Site A only.

6.1.2.2 Discussion

The range of MADF concentrations recorded was from 27.0% to 33.5% or about 73.7% to 60.2% D value (Table 11). This indicates that the management scheme adopted was successful in maintaining the production of moderate to good quality herbage with respect to its digestibility.

The most marked effect of the N sources on the MADF concentration of the grass was in cut 3, 1979, at Site A and in cut 2, 1980, at both sites. The common feature of all three site/cuts is that the DM yield from the control plots was very low and they followed cuts in which a large amount of DM had been removed. It is likely that low digestibility litter and stubble from these heavy cuts was recovered in the subsequent cut. The large negative and non-linear effect of the application of the N sources was probably due to the decrease in proportion of this dead material in the harvested grass as the N supply and DM yield increased.

Table 31 The Analysis of the Response of the Concentration of MADF in the Grass to the Applications of AN, LDS and LAS

Source	Component	Cut No							
		1		2		3		4	
		Site							
		A	B	A	B	A	B	A	B
					1979				
AN	LIN	NS	**	NS	NS	***	**	NS	*
	QUAD	NS	NS	NS	NS	**	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	NS	NS	NS	NS	***	NS	NS	NS
	QUAD	NS	NS	NS	NS	*	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	**	NS	NS	NS	***	NS	NS	NS
	QUAD	NS	NS	NS	NS	**	*	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
					1980				
AN	LIN	NS	NS	***	***	NS	NS	*	NS
	QUAD	NS	NS	NS	**	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	*	NS
LDS	LIN	*	NS	**	***	NS	NS	NS	NS
	QUAD	NS	NS	NS	**	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	**	NS	***	***	NS	NS	NS	NS
	QUAD	NS	NS	**	**	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS

The low CP concentration in the grass receiving little or no supplementary N may also have contributed to this effect (Whitehead, 1970).

The increases in the concentration of MADF due to one or more of the N sources which occurred in cut 1, 1979, at both sites and in cut 1, 1980, at Site A were probably due to an interaction between N supply and reproductive growth resulting in an increase in the proportion of stem in the crop.

The small decreases in the concentration of MADF in cut 3 and 4, 1979, at Site B following the application of AN may have been due to an increase in the CP content. However, if this was so, it is curious that the application of AN did not have an effect on the concentration of MADF in more site/cuts.

The reason for the effect on the concentration of MADF of the application of AN in cut 4, 1980, at Site A and of LAS in cut 3, 1979, at Site B is unclear.

The MADF results from the nine site/cuts in which there was a significant ($p < 0.05$) response to the application of one or more of the N sources were plotted against the N yield results to determine whether the relationships between the AN and sludge effects could be accounted for by the supply of N (Fig 39 and 40).

The plots were visually assessed to determine whether the relationships derived from the effects of the AN, LDS and LAS were coincident. This was considered to be so in all site/cuts except cut 1, 1979, at Site A and cut 4, 1979, at Site B. The plot of results from cut 3, 1979, at Site B was considered too variable to draw any conclusion.

The displacement of the AN treatment effects away from those of the sludge treatments in cut 1 in 1980 at Site A probably reflects the stimulation of new growth in the spring following winterkill of the sward. The absence of a similar effect in cut 1, 1979, at this site may have been due to the inclusion of dead material in the crop as the

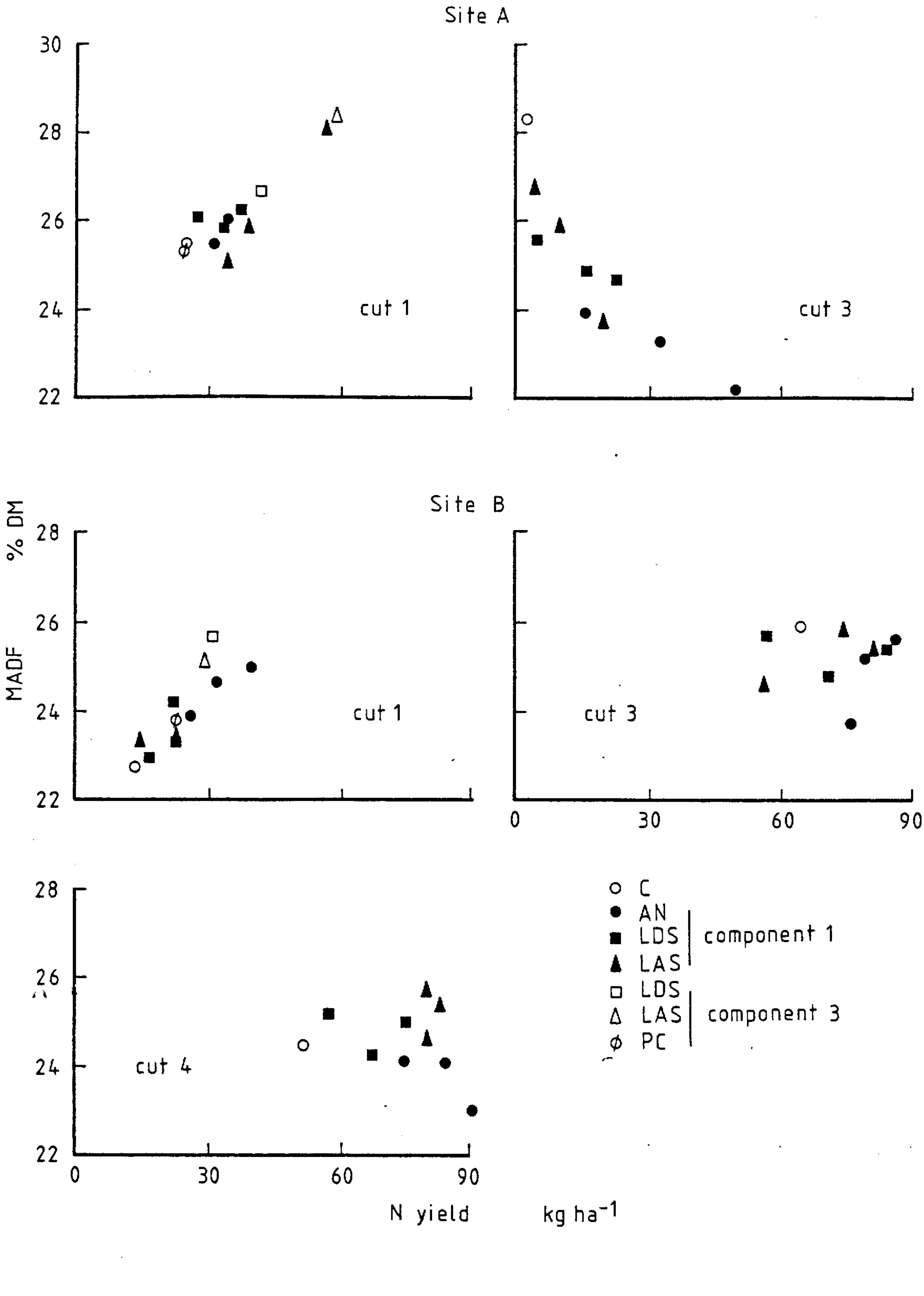


Fig 39 The relationship between MADF and N yield in 1979

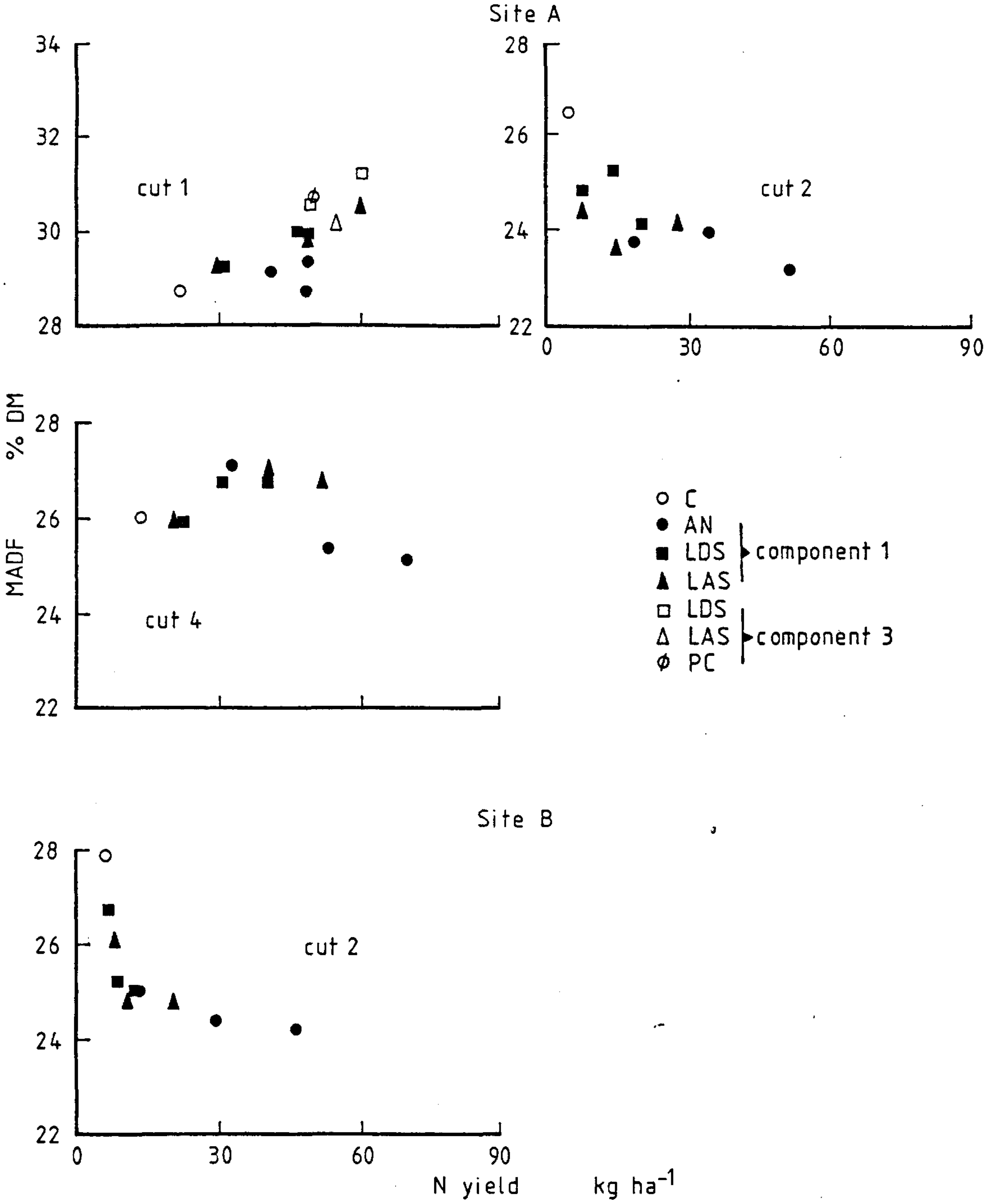


Fig 40 The relationship between MADF and N yield in 1980.

topping cut taken in early February 1979 was less efficient than a similar cut taken in November of the same year.

The plot of MADF v N yield results from cut 4, 1979, at Site B suggests that the concentration of MADF in the grass cut from the plots receiving LAS and to a lesser extent the LDS was about 0.5 to 1.0% MADF higher than could be accounted for by the N supply. Given the sparcity of the results, it is not possible to determine the significance of this discrepancy or its origin.

The results of this field trial suggest that the digestibility of the grass is more sensitive to applications of sludges than has previously been found (King and Morris, 1972, Edgar et al., 1981). Differences in experimental technique and particularly differences in sward management may explain the difference in results between this and earlier investigations.

The discrepancies between the relationships derived from the AN and sludge effects described above did not exceed 1% MADF. It is unlikely that a difference of this magnitude would be detected under normal farming conditions and so for advisory purposes the effects of the sludge and the AN on digestibility can be considered as the same when supplying the same amount of available N.

6.1.3 Water soluble carbohydrate

6.1.3.1 Results

The concentration of WSC in the grass harvested from plots receiving the Component 1 treatments is given in Table 32 and 33.

A response analysis found a significant (p 0.05) negative response to the application of AN in cut 1 in both years and sites, cut 2 in both years at Site A and in cut 4, 1979, and cut 3, 1980, at Site B (Table 34). There was a significant ($p < 0.05$) negative response to the application of LDS in cut 1 and 2 in both years at Site A and in cut 2, 1979, at Site B. There was a significant ($p < 0.05$) negative

Table 32 The Concentration of WSC in the Grass in 1979

Treatment	WSC % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	25.5	38.3	23.6	16.3	15.7	18.0	19.3	20.7
AN1	22.2	33.2	23.4	15.7	20.7	18.6	18.6	17.6
AN2	18.7	27.0	20.9	13.7	20.0	16.6	19.2	18.6
AN3	15.7	24.4	16.5	11.5	16.0	17.0	16.9	15.7
LDS1	24.0	37.3	24.7	17.3	18.7	19.0	19.1	20.3
LDS2	20.8	32.6	23.4	15.7	18.6	18.0	19.5	20.1
LDS3	21.6	30.9	22.3	15.0	19.2	15.7	18.0	19.0
LAS1	28.2	35.3	25.0	16.9	17.5	17.9	18.9	18.0
LAS2	22.0	33.7	24.3	15.2	18.9	17.1	18.6	18.7
LAS3	17.8	32.0	24.9	19.1	18.6	17.3	17.8	18.3

Table 33 The Concentration of WSC in the Grass in 1980

Treatment	WSC % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
C	23.4	18.9	18.6	20.7	9.7	9.4	17.2	15.9
AN1	18.7	16.0	19.8	23.2	7.7	16.6	15.9	17.6
AN2	17.0	14.5	16.8	20.9	8.6	14.9	16.4	17.4
AN2	14.8	12.7	14.9	18.9	7.4	10.6	16.6	17.2
LDS1	21.4	17.3	20.4	23.5	11.0	14.7	15.8	17.6
LDS2	19.6	17.6	18.4	22.2	8.4	15.6	16.9	17.6
LDS3	18.2	15.7	17.0	24.0	11.0	17.2	17.6	22.1
LAS1	21.3	17.7	19.5	21.4	8.6	18.4	16.9	15.9
LAS2	19.2	15.9	18.9	22.3	5.6	15.8	15.5	18.6
LAS3	19.9	16.2	16.8	21.4	6.7	13.5	14.5	15.3

Table 34 The Analysis of the Response of the Concentration of WSC in the Grass to Applications of AN, LDS and LAS

Source	Component	Cut No							
		1		2		3		4	
		Site							
		A	B	A	B	A	B	A	B
					1979				
AN	LIN	***	***	***	NS	NS	NS	NS	**
	QUAD	NS	NS	NS	NS	***	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	**	***	NS	NS	***	NS	NS	NS
	QUAD	NS	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	***	**	NS	NS	***	NS	NS	NS
	QUAD	**	NS	NS	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
					1980				
AN	LIN	***	***	***	NS	NS	**	NS	NS
	QUAD	NS	NS	*	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LDS	LIN	**	NS	*	NS	NS	NS	NS	NS
	QUAD	NS	NS	*	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS
LAS	LIN	*	*	NS	NS	NS	*	NS	NS
	QUAD	NS	NS	*	NS	NS	NS	NS	NS
	RESID	NS	NS	NS	NS	NS	NS	NS	NS

response to the application of LAS in cut 1 in both years and at both sites, in cut 2 in both years at Site A and cut 3, 1980, at Site B. In cut 3, 1979, at Site A the response to the application of LDS and LAS was significantly ($p < 0.001$) linear and positive whereas that to AN was significantly ($p < 0.001$) quadratic and both positive and negative.

6.1.3.2 Discussion

The concentration of WSC in the grass only fell below the 10% level required for silage making without additives (NIAB, 1978) in cut 3, 1980, at Site A.

The low values obtained in this one cut may be erroneous as a drier malfunction led to some of the grass samples being heated above 100°C.

The effect of the treatment on the concentration of WSC was small except in cut 1, 1979, at both sites (Table 32 and 33). The greater effect of the N source applications in this cut may be attributed to an interaction between N supply and reproductive growth plus the delay in commencement of grass growth due to the cool, wet weather.

Previous investigations have found applications of N to reduce the WSC concentration in grass due to the stimulation of growth (Whitehead, 1970). A similar reduction was found in half of the site/cuts in this trial. The apparent increases in the concentration of WSC with increasing N yield which occurred in cut 3, 1979, at Site A and in cut 2, 1980, at Site B were probably caused by the inclusion of a high proportion of litter in the grass removed from the plots receiving no or little available N (Fig 12 and 15).

The WSC results from the 9 site/cuts in which there was a significant ($p < 0.05$) response to one or more source of N (Table 34) were plotted against the N yield results (Fig 41 and 42). The plots were visually assesed to determine whether the relationships between WSC and N yield derived from the application of AN, LDS and LAS were coincident. This was considered

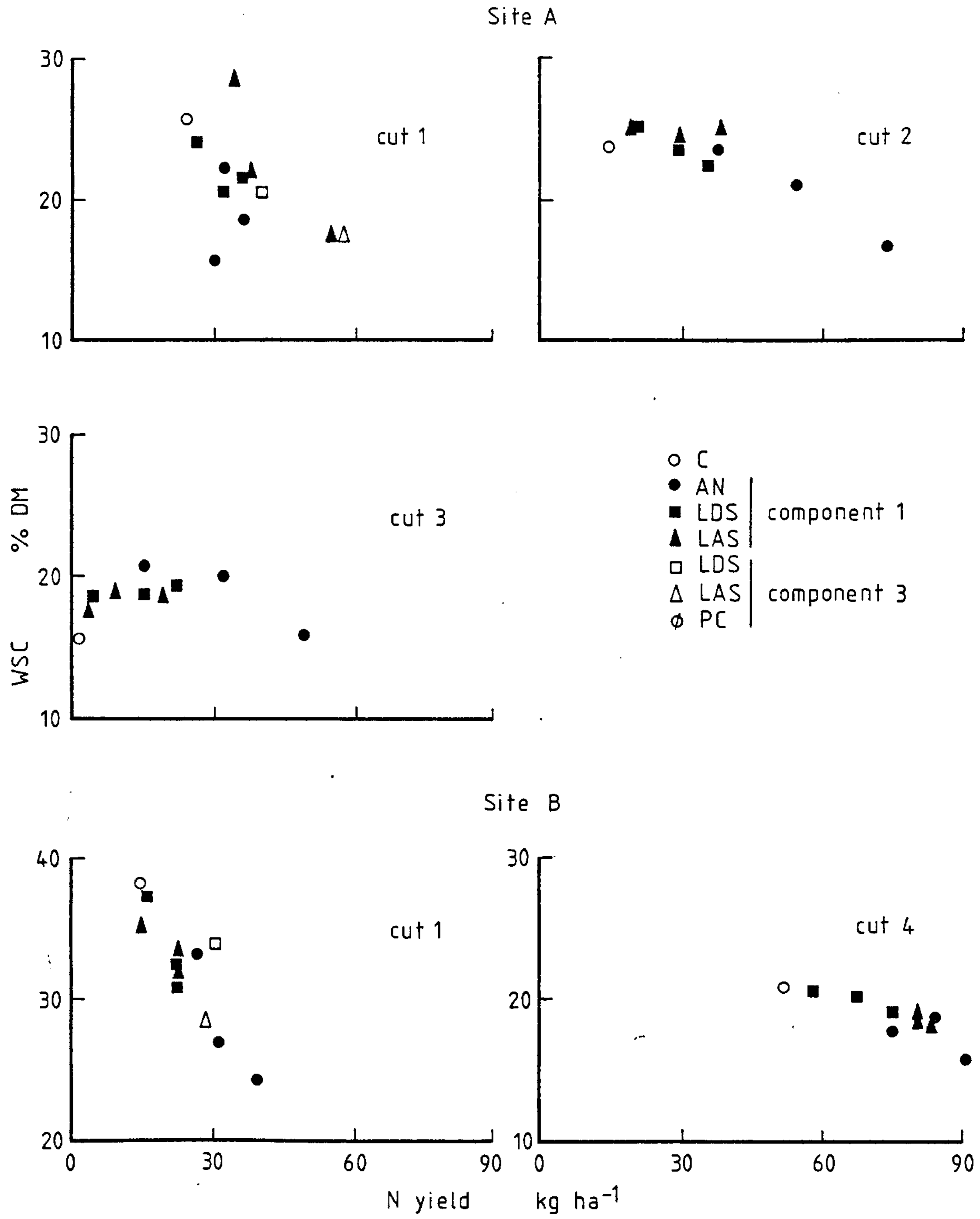


Fig 41 The relationship between WSC and N yield in 1979.

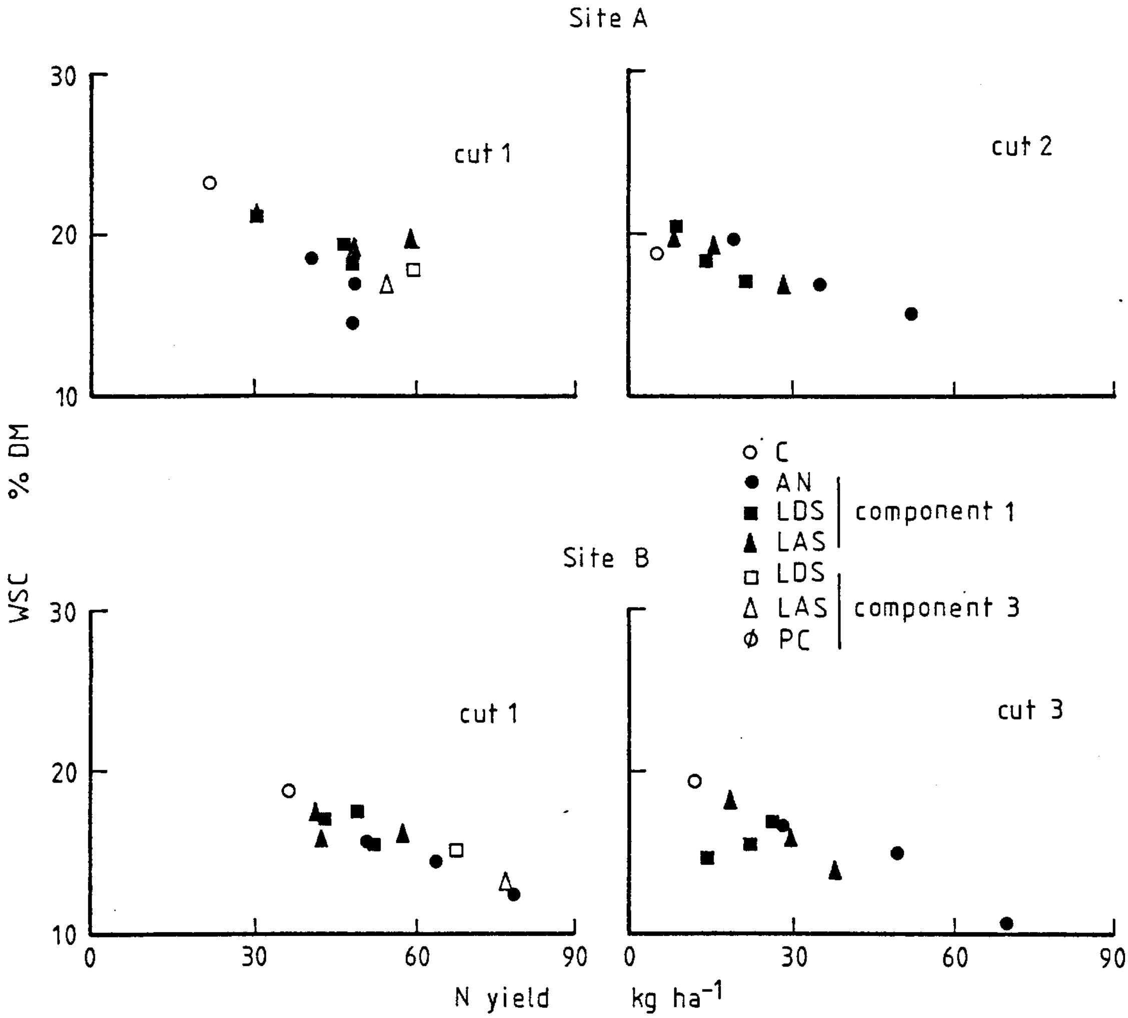


Fig 42 The relationship between WSC and N yield in 1980.

to be so in all site/cuts except cut 1 in both years at Site A. These discrepancies were probably due to the inclusion of dead material in the grass removed from the AN plots (p 90). The reduced amount of living grass remaining on these plots following the winterkill would also have been very intensely fertilized, further reducing the concentration of WSC in the crop.

These results suggest that provided the ability of the sward to respond to N has not been selectively reduced by winterkill, the effect of the application of LDS and LAS on the concentration of WSC in the grass will be similar to that of an application of AN supplying the same amount of available N.

6.1.4 Nitrate-nitrogen

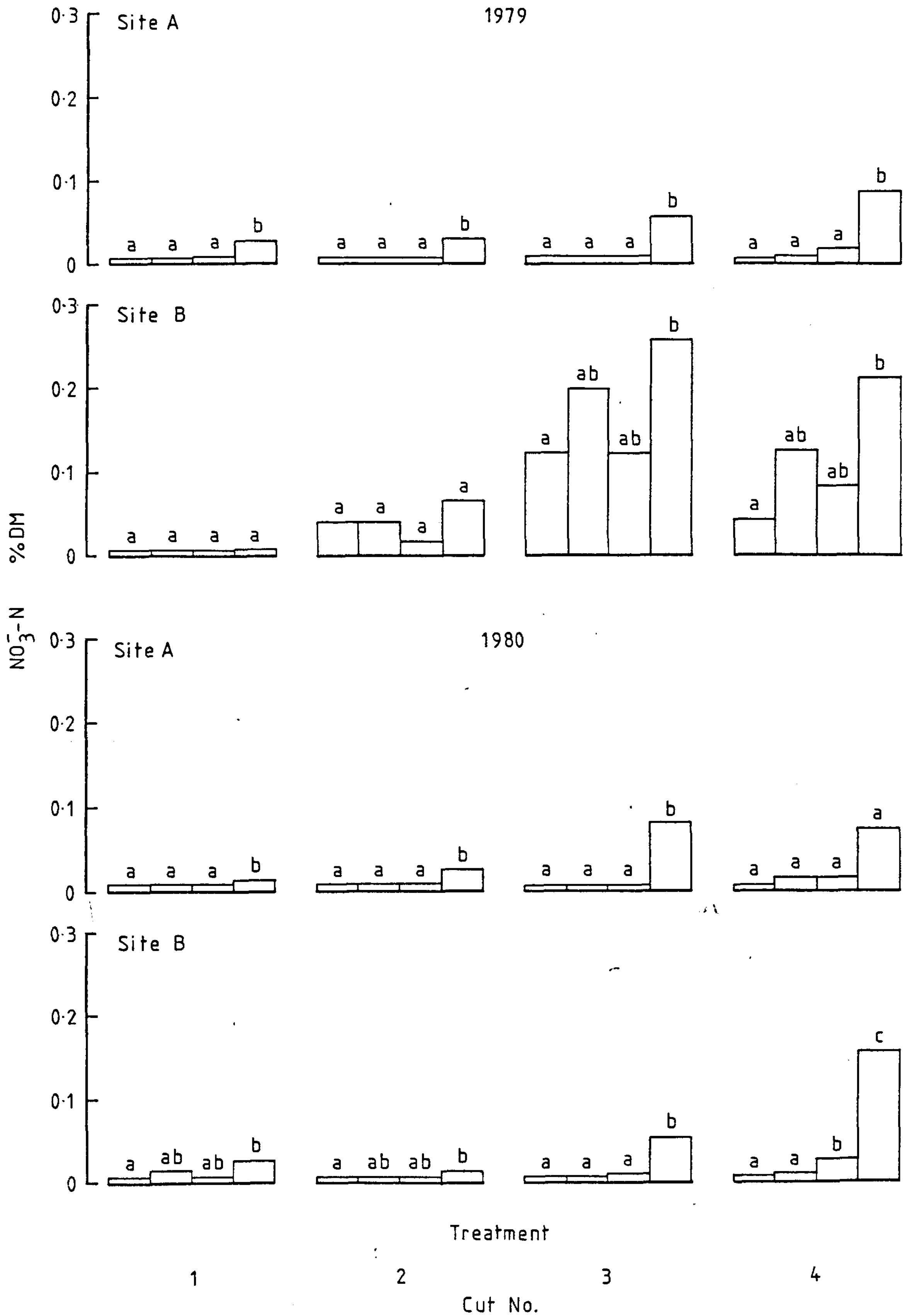
6.1.4.1 Results

The concentration of NO_3^-- N in the grass harvested from plots receiving the C, LDS3, LAS3 and AN3 treatments is shown in Fig 43.

An initial inspection of the results suggested that they were not normally distributed. A log transformation appeared to normalize the distribution so subsequent statistical analysis used the log transformed results.

An analysis of variance found significant ($p < 0.05$) difference between the treatment effects in 13 of the site/cuts. The significance of the differences between individual treatment effects was determined using Tukey's W procedure (Fig 43).

The effect of the treatment on the NO_3^-- N concentration increased as the growing season progressed and was usually greater at Site B than at Site A. The concentration of NO_3^-- N was greatest in the grass receiving the AN3 treatment and least in the grass receiving the C treatment. The concentration of NO_3^-- N in the grass receiving the sludge treatments was not significantly ($p < 0.05$) different from that in grass cut from the control plots except in cut 4, 1980, at Site B



Treatment effects bearing the same letter within a site/cut are not significantly different ($P > 0{\cdot}05$)

Fig 43 The effect of treatments C, LDS3, LAS3 and AN3 on the grass NO_3^--N concentration.

when the effect of the LAS3 treatment was significantly ($p < 0.05$) different from the control.

6.1.4.2 Discussion

The NO_3^-- N concentration in the grass was below the potentially toxic concentration of 0.4% NO_3^-- N suggested by Wright and Davison (1964) in all site/cuts (Fig.43)

The increases in the NO_3^-- N concentration as the growth season progressedwere probably due to the reduction in E_N (Fig 35 and 36). The higher NO_3^-- N concentration in the grass at Site B compared to Site A was probably due to the higher soil N supply (Fig. 18 and 19). The effect of the treatments appeared to increase non-linearly with the increase in the availability of the N in the source applied. This observation is supported by the non-linear increase in NO_3^-- N concentration with increasing application rate of inorganic N fertilizer which was reported by Reid (1966) and Ennik et al. (1980).

There was no indication that a slow release of sludge N was increasing the NO_3^-- N concentration in the grass above that which would be expected from AN supplying the same amount of available N. This suggests that the concentration of NO_3^-- N in grass treated with liquid sludges is unlikely to reach the toxic threshold provided the application rate is designed to supply the N requirement of the crop and unless the soil N supply is very high.

6.1.5 Calcium and magnesium

6.1.5.1 Results

The concentration of Ca and Mg in the grass from plots receiving the AN3, LAS3, LDS3 and C treatments is given in Tables 35 and 36. respectively.

The results were analysed by two-way analysis of variance within each site/cut. The significance of the differences between individual treatment effects was determined by Tukey's W procedure.

The treatments had little effect on the concentration of Ca and Mg in the grass. The AN3 treatment significantly ($p < 0.05$) increased the concentration of Ca in cut 4, 1980, at Site A and in cut 2, 3 and 4, 1979, at Site B and significantly ($p < 0.05$) increased the concentration of Mg in cut 2 and 4, 1980, at Site A and cut 2 and 3, 1979, at Site B. In cut 2, 1980, at Site B the LDS3 treatment significantly ($p < 0.05$) depressed the concentration of Mg below that of the C and AN3 treatment effects.

Table 35 The Concentration of Ca in the Grass from Plots receiving the AN3, LDS3, LAS3 and C Treatments

Treatment	Ca Concentration % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
	1979							
AN3	0.40	0.25	0.29	0.18b	0.45	0.37b	0.41	0.36b
LDS3	0.37	0.21	0.22	0.15a	0.41	0.29a	0.36	0.28ab
LAS3	0.38	0.19	0.22	0.15a	0.38	0.27a	0.33	0.26a
C	0.32	0.21	0.21	0.14a	0.41	0.27a	0.40	0.22a
SIGN	NS	NS	NS	**	NS	***	NS	**
	1980							
AN3	0.35	0.23	0.53	0.38	0.36	0.21	0.42b	0.24
LDS3	0.31	0.18	0.48	0.29	0.37	0.27	0.27a	0.21
LAS3	0.29	0.24	0.46	0.34	0.34	0.22	0.27a	0.20
C	0.27	0.18	0.48	0.35	0.35	0.23	0.30a	0.22
SIGN	NS	NS	NS	NS	NS	NS	**	NS

Treatment effects bearing the same letter within a site/cut were not significantly (p 0.05) different.

Table 36 The Concentration of Mg in the Grass from Plots receiving the AN3, LAS3, LDS3 and C Treatments

Treatment	Mg Concentration % DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
				1979				
AN3	0.12	0.12	0.11	0.18b	0.16	0.33b	0.16	0.27
LDS3	0.12	0.10	0.11	0.15a	0.16	0.26a	0.16	0.25
LAS3	0.12	0.09	0.11	0.15a	0.16	0.26a	0.18	0.23
C	0.11	0.09	0.11	0.15a	0.15	0.26a	0.16	0.22
SIGN	NS	NS	NS	*	NS	***	NS	NS
				1980				
AN3	0.14	0.17	0.21b	0.18b	0.19	0.15	0.21b	0.19
LDS3	0.13	0.14	0.19ab	0.15a	0.20	0.17	0.18ab	0.18
LAS3	0.14	0.18	0.19ab	0.16ab	0.17	0.17	0.17a	0.18
C	0.12	0.12	0.16a	0.18b	0.18	0.18	0.17a	0.20
SIGN	NS	NS	*	*	NS	NS	*	NS

Treatment effects bearing the same letter within a site/cut were not significantly ($p > 0.05$) different.

6.1.5.2 Discussion

The manner in which the treatments usually affected the concentration of Ca and Mg in the grass (AN > sludges > C) suggests that the small and often not significant ($p > 0.05$) increases recorded were due to a stimulation of root growth or activity following the application of available N.

The increases in the concentration of Ca in the grass following the application of either AN or the sludges were similar to those found by Soon et al. (1978) although Coker (1966) found no such effects. The higher pH (7.7-7.8) at Coker's site suggests that a very good supply of Ca may have masked any sludge or fertilizer effects. The small increases in the concentration of Mg in the grass following the application of AN or (in most site/cuts) the sludges were similar to the findings of both Coker (1966) and Soon et al. (1978). The small but significant ($p < 0.05$) depression of the concentration of Mg and not significant ($p < 0.05$) depression of the concentration of Ca in cut 2, 1980, at Site B may indicate that the grass absorbed the LDS N predominantly as NH_4^+- N, thereby reducing cation uptake (Viets, 1965). However, there is no apparent reason why nitrification of the LDS NH_4^+- N should have been inhibited in this particular growth period.

The small change in the concentration of Ca and Mg in the grass following sludge applications found in this and other trials suggests that for practical purposes the effect of the sludges can be ignored.

6.1.6 Potentially toxic elements

6.1.6.1 Results

The concentration of Zn, Cu, Ni and Pb in the grass harvested from plots receiving the AN3, LDS3, LAS3 and C treatments is given in Tables 37 to 40.

Where the concentration of Ni or Pb in one replicate of a treatment was below the detection limit, the value displayed in Table 39 and 40 was calculated as if the concentration in that replicate was at the detection limit. Treatment effects in which two or more replicates were below the detection limit are shown as <detection limit. The concentration of Cr in grass harvested from plots receiving the LDS3 treatment in cut 4, 1979, at Site A was 3.3 mg kg^{-1} DM. The concentration of Cr in the remainder of the site/cuts and the concentration of Cd in all site/cuts was below the detection levels of 3 and 1 mg kg^{-1} DM respectively.

Table 37 The Concentration of Zn in Grass receiving the AN3, LDS3, LAS3 and C Treatments

Treatment	Zn Concentration mg Zn kg^{-1} DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
	1979							
AN3	39.0	23.0	27.0	34.0	35.3ab	40.8	62.0b	48.0
LDS3	32.8	23.3	28.0	28.3	37.5b	45.8	51.0b	55.0
LAS3	26.3	23.0	25.8	29.0	30.5ab	52.0	34.0a	41.5
C	27.0	14.0	20.8	29.5	23.8a	40.8	32.8a	33.8
SIGN	NS	NS	NS	NS	*	NS	*	NS
	1980							
AN3	33.5	23.0	37.8bc	28.0bc	42.5b	29.5ab	34.3b	36.3
LDS3	33.5	25.0	43.0c	29.8c	52.0c	51.3c	42.5c	33.8
LAS3	28.5	23.0	33.8b	24.5b	34.0ab	30.3b	31.3b	28.5
C	20.0	19.8	21.8a	20.3a	21.8a	21.8a	22.8a	31.3
SIGN	NS	NS	***	***	**	***	***	NS

Treatment effects bearing the same letter within a site/cut were not significantly ($p < 0.05$) different.

Table 38 The Concentration of Cu in Grass receiving the AN3, LAS3, LDS3 and C Treatments

Treatment	Cu Concentration mg Cu kg^{-1} DM							
	Cut No							
	1		2		3		4	
	Site							
	A	B	A	B	A	B	A	B
				1979				
AN3	6.5	5.8b	5.8ab	5.8	6.3	9.8	18.0b	15.8
LDS3	6.5	4.8ab	5.5b	5.5	8.0	12.5	14.3ab	19.8
LAS3	7.5	3.8a	5.0ab	5.8	9.3	14.3	10.8a	21.3
C	6.0	3.8a	4.3a	5.0	4.3	13.8	11.9a	12.3
SIGN	NS	*	**	NS	NS	NS	*	NS
				1980				
AN3	5.0	5.3	9.3ab	8.5b	10.3	9.5a	5.3a	9.5
LDS3	5.3	5.0	10.3b	9.5b	10.8	15.5b	8.0b	8.5
LAS3	7.3	6.5	8.5ab	7.8b	11.5	9.0a	7.8b	10.0
C	4.8	4.5	5.5a	5.5a	7.8	6.3a	4.8a	8.8
SIGN	NS	NS	**	***	NS	**	***	NS

Treatment effects bearing the same letter within a site/cut were not significantly (p 0.05) different.

Table 39 The Concentration of Ni in Grass receiving the AN3, LDS3, LAS3 and C Treatments

<table>
<tr><th rowspan="5">Treatment</th><th colspan="8">Ni Concentration mg Ni kg^{-1} DM</th></tr>
<tr><th colspan="8">Cut No</th></tr>
<tr><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th></tr>
<tr><th colspan="8">Site</th></tr>
<tr><th>A</th><th>B</th><th>A</th><th>B</th><th>A</th><th>B</th><th>A</th><th>B</th></tr>
<tr><td></td><td colspan="8">1979</td></tr>
<tr><td>AN3</td><td rowspan="4"><3</td><td rowspan="4"><3</td><td rowspan="4"><3</td><td rowspan="4"><3</td><td rowspan="4"><3</td><td>5.8*</td><td rowspan="4"><3</td><td rowspan="4"><3</td></tr>
<tr><td>LDS3</td><td><3</td></tr>
<tr><td>LAS3</td><td>5.0*</td></tr>
<tr><td>C</td><td><3</td></tr>
<tr><td>SIGN</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td></tr>
<tr><td></td><td colspan="8">1980</td></tr>
<tr><td>AN3</td><td><1</td><td><1</td><td rowspan="4"><1</td><td rowspan="4"><1</td><td><1</td><td><1</td><td rowspan="4"><1</td><td rowspan="4"><1</td></tr>
<tr><td>LDS3</td><td>1.3*</td><td><1</td><td>2.8*</td><td><1</td></tr>
<tr><td>LAS3</td><td><1</td><td>3.0</td><td><1</td><td>2.0*</td></tr>
<tr><td>C</td><td><1</td><td>3.8*</td><td><1</td><td><1</td></tr>
<tr><td>SIGN</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td></tr>
</table>

* One replicate <3 mg kg^{-1} DM (1979) or <1 mg kg^{-1} DM (1980) See text.

Table 40 The Concentration of Pb in Grass receiving the AN3, LDS3, LAS3 and C Treatments

<table>
<tr><th rowspan="5">Treatment</th><th colspan="8">Pb Concentration mg Pb kg^{-1} DM</th></tr>
<tr><th colspan="8">Cut No</th></tr>
<tr><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th></tr>
<tr><th colspan="8">Site</th></tr>
<tr><th>A</th><th>B</th><th>A</th><th>B</th><th>A</th><th>B</th><th>A</th><th>B</th></tr>
<tr><td></td><td colspan="8">1979</td></tr>
<tr><td>AN3</td><td rowspan="4"><4</td><td rowspan="4"><4</td><td rowspan="4"><4</td><td rowspan="4"><4</td><td><4</td><td rowspan="4"><4</td><td>6.3a</td><td>5.5*</td></tr>
<tr><td>LDS3</td><td>10.0</td><td>10.8b</td><td>8.0</td></tr>
<tr><td>LAS3</td><td><4</td><td>6.8a</td><td>4.0*</td></tr>
<tr><td>C</td><td>5.3*</td><td>7.3ab</td><td>4.0*</td></tr>
<tr><td>SIGN</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>*</td><td>ND</td></tr>
<tr><td></td><td colspan="8">1980</td></tr>
<tr><td>AN3</td><td rowspan="4"><4</td><td rowspan="4"><4</td><td><4</td><td><4</td><td><4</td><td><4</td><td><4</td><td rowspan="4"><4</td></tr>
<tr><td>LDS3</td><td>4.5*</td><td>4.5</td><td>6.8*</td><td>8.5*</td><td>5.3*</td></tr>
<tr><td>LAS3</td><td><4</td><td><4</td><td><4</td><td><4</td><td>6.3</td></tr>
<tr><td>C</td><td><4</td><td><4</td><td><4</td><td><4</td><td>4.3*</td></tr>
<tr><td>SIGN</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td><td>ND</td></tr>
</table>

* One replicate <4 mg kg^{-1} DM. See text.

Treatment effects bearing the same letter within a site/cut were not significantly (p 0.05) different.

The results of the effect of the treatments on the concentration of an element were analysed by a two-way analysis of variance for those site/cuts in which all replicates were above the detection limit. The significance of the difference between individual treatment effects was determined by Tukey's W procedure.

There was a trend towards an increase in the Zn, Cu and Pb concentrations in the grass as the growing season progressed (Tables 37, 38 and 40). The AN3 treatment tended to increase the concentration of Zn although this effect was only significant ($p < 0.05$) in five site/cuts. There was a similar effect on the concentration of Cu but this was significant ($p < 0.05$) in only three site/cuts. Both the LDS3 and LAS3 treatments also tended to increase the concentration of Zn and Cu. The effect of the LAS3 treatment on the concentration of Zn and Cu was usually similar or not significantly ($p < 0.05$) different from that of the AN3 treatment. In cut 4, 1979, at Site A the effect of the AN3 treatment was significantly ($p < 0.05$) greater than that of the LAS3 treatment. The effect of the LDS3 treatment on the concentration of Zn was usually greater than that of the AN3, significantly ($p < 0.05$) so in cuts 2, 3 and 4, 1980, at Site A and cut 3, 1980, at Site B. The effect of the LDS 3 treatment on the concentration of Cu was similar or greater than that of the AN3 treatment in most site/cuts, significantly ($p < 0.05$) greater in cut 4, 1980, at Site A and cut 3, 1980, at Site B. The LDS3 treatment also elevated the concentration of Pb above the detection limit (4 mg kg^{-1} DM) in more site/cuts than any other treatment and significantly ($p < 0.05$) increased the Pb concentration in cut 4, 1979, at Site A above that in the grass receiving the AN3 or LAS3 treatments. There was no obvious pattern in the effect of the treatments on the concentration of Ni in the grass (Table 39).

6.1.6.2 Discussion

A trend towards an increase in the concentration of Zn, Cu and Pb in the grass as the growing season progressed (Tables 37, 38 and 40) was noted by Nelmes et al. (1974) and Unwin (1980). A reduction in the diluting effect of DM yield increases may be responsible. However, the application of AN, whilst increasing DM yield, also increased the concentration of Zn and Cu in several site/cuts. Whitehead (1970) concluded that applications of N fertilizers may increase the concentration of Zn and Cu but that increases in the concentration of Zn were unlikely at the rates of application of N used in this field trial. These results indicate that an N effect on the concentration of Zn is possible at lower intensities of N fertilization.

The effect of the LAS3 treatment on the concentration of Zn and Cu (Table 37 and 38) was consistent with that predicted by an effect of sludge N, given the lower availability of the LAS N in comparison with that of the AN (Table 15). In contrast the effect of the LDS3 treatment on the concentration of both Zn and Cu was greater than could be accounted for by the supply of available N. These elevated concentrations of Zn and Cu were associated with elevated concentrations of Pb (Table 40) and (in cut 4, 1979, at Site A) of Cr. As the concentrations of Cu, Pb and Cr are not readily increased by the application of these elements to the soil, this suggests that the elevated PTE concentrations were due to either contamination of the samples with sludge amended soil or to sludge solids adhering to the grass leaves or to the absorption of PTE's onto the leaf surface.

Some soil contamination is inevitable when grass is raked into heaps during harvesting. However it is unlikely that this was a major pathway by which PTE's appeared in the harvested grass. The same harvesting procedure was used on the LDS and LAS treated plots, yet there was no marked increase in the PTE concentrations in the LAS treated grass despite the high PTE concentration in this sludge (Table 7) compared to that of uncontaminated grass (Table 6). The absorption of PTE's to the leaf surface would also have been expected to lead to a greater increase in the concentration of PTE's in the LAS treated grass than was observed. Consequently, it is probable that the elevation of the concentration of PTE's in grass treated with LDS was due to the adherance of sludge solids to the grass leaves. This was confirmed by observation during the harvesting of cut 3, 1980, at both sites.

In the field it was observed that there were substantial differences in the amount of foliar retention of sludge solids both between the LDS and LAS and between sludges of different solids contents, within a sludge type. This was examined more closely in a pot experiment (Appendix 6). The relationship between the maximum foliar retention capacity for sludge solids and the type and solids content of the sludge which was obtained in this experiment is shown in Fig 44. Given the mean solids content of the LDS and LAS used in the field trial was 5.3% and 2.2% respectively, the relationship predicts that the initial foliar retention of the solids from a LDS of mean solids content would have been 7 to 10 times greater than that of a LAS of mean solids content. The LAS solids did not appear to be as tightly bound to the grass leaves as those of the LDS and this may have further increased the difference between the foliar retention of the solids of the two sludge types at the time of harvesting.

The concentration of Zn and Cu in the grass was very sensitive to the presence of sludge solids. For example, the mean amount of Zn and Cu present in an application of LDS supplying 75 kg total N ha^{-1} was about 2400 g and 760 g respectively. If 1% of the sludge Zn and Cu was retained on the leaves of a nominal 2 t DM crop of grass, the rise in the concentration of Zn and Cu in the crop would have been 12 and 3.8 mg kg^{-1} DM respectively. Given the substantial foliar retention of solids which is observed at the time of application, it is surprising that the concentrations of PTE's in the grass were not greatly increased. The mechanism(s) by which sludge solids are dislodged from grass leaves have yet to be defined (p 30). These mechanisms are worthy of

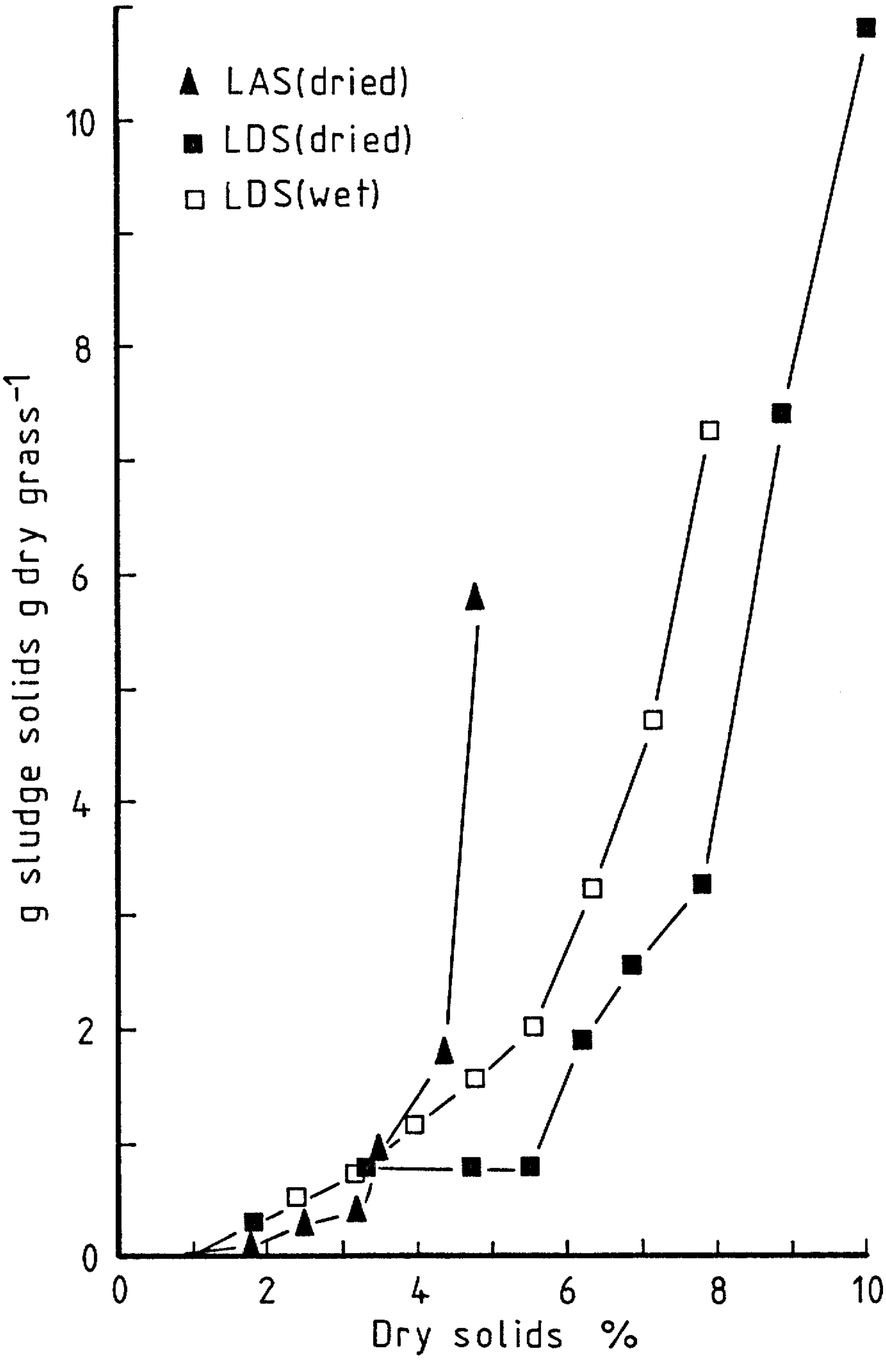


Fig 44 The relationship between foliar sludge retention and the dry solids content of the liquid sludges.

investigation since alterations to the minimum period between sludge application and harvesting or livestock grazing may be required to allow sufficient time for the mechanisms to act. The death and subsequent detachment of sludge-bearing leaf fragments, the flaking off of solids as the leaf flexes and the abrasive action of leaf on leaf through the action of the wind are pathways for the reduction of foliar retention that have yet to be examined.

The interpretation of the effect of the treatments on the concentration of Ni in the grass (Table 39) is hindered by the low levels present (compare with Table 6). The origin of the occasional treatment effect remains obscure.

The application of the liquid sludges increased the concentration of Cu in several site/cuts and in one site/cut Cr above that normally found in plant tissue although in several site/cuts the concentration of Cu was below that required for good dairy cow nutrition (10 mg kg^{-1} DM). The increases in the concentration of Cu which resulted from both the AN3 and sludge treatments did not lower the value of the grass as a feed for cattle but may in cut 4, 1979, at both sites and cut 3, 1980, at Site B have produced grass unsuitable for feeding to sheep (Dam Kofoed, 1981). The availability to livestock of the Cu in sludge solids is not known although the experience with Cu in animal manures is that it is less available than Cu absorbed by grass (Gracey et al., 1976).

The concentration of PTE's other than Cu and Cr was not increased above the normal range. Other investigations have found greater increases in the concentrations of PTE's in grass following surface applications of sludge (Chaney and Lloyd, 1979, Webber, 1980). Until further information concerning the factors affecting the foliar retention of sludge solids becomes available, the importance of this effect as a pathway for the transfer of sludge PTE's to animals remains uncertain.

6.2 Component 3 treatment effects

6.2.1 All parameters

6.2.1.1 Results

The effect of the Component 3 treatment on the quality of the grass harvested in cut 1 of both years and at both sites is given in Table 41, 42 and 43. The effects of the C and AN3 treatments are included for comparison.

The significance of the differences between individual Component 3 treatment effects and those of the C and AN3 treatment was determined by Tukey's W procedure.

The effect of the Component 2 treatment on the concentration of CP, MADF and WSC increased in the order PC < LDS s < LAS s although the effects of the PC and LDS s treatments were similar in 1980 (Table 41). Differences between the effects of the Component 3 treatment were rarely significant ($p < 0.05$). The effect of the Component 3 treatments on the concentration of CP and WSC was intermediate between those of the C and AN3 treatments. However, the effects of the LDS(s) and LAS(s) treatments in 1979 and all Component 3 treatments in 1980 on the concentration of MADF were greater than that of the AN3 treatment.

The Component 3 treatment did not significantly ($p < 0.05$) increase the concentration of NO_3^-- N, Ca, Mg, Cu or Zn above that of the C treatment (Tables 42 and 43). The concentration of Cd, Cr and Pb was not raised above the detection limits of 1, 3 and 4 mg kg^{-1} DM respectively. The LDS(s) and LAS(s) treatments may have increased the concentration of Ni in 1980 at both sites.

6.2.1.2 Discussion

The amount of sludge required to supply about 150 kg N ha^{-1} was quite large (about 100 m^3 ha^{-1} or about 5 t dry solids LDS and 3 t dry solids LAS) but had little effect on the quality of the grass. The

Table 41 The Effect of Component 3 Treatments on the CP, MADF, WSC and NO_3^- - N Content of Grass harvested in Cut 1 of 1979 and 1980

	Site A					Site B				
	Cut 1, 1979									
CP	C	PC	LDS(s)	LAS(s)	AN3	C	PC	LDS(s)	LAS(s)	AN3
% DM	12.3	12.8	13.3	13.9	19.0	8.5	8.9	9.8	11.1	15.7
MADF	PC	C	AN3	LDS(s)	LAS(s)	C	PC	AN3	LAS(s)	LDS(s)
% DM	25.3	25.4	25.4	26.6	28.3	22.8	23.8	25.1	25.1	25.7
WSC*	AN3	LAS(s)	LDS(s)	C		AN3	LAS(s)	LDS(s)	C	
% DM	15.7	17.8	20.6	25.5		24.4	28.7	34.1	38.3	
NO_3^- - N*	C	LDS(s)	LAS(s)	AN3		C	LAS(s)	LDS(s)	AN3	
% DM	0.007	0.007	0.008	0.026		0.006	0.006	0.008	0.008	
	Cut 1, 1980									
CP	C	LDS(s)	PC	LAS(s)	AN3	C	LDS(s)	PC	LAS(s)	AN3
% DM	7.7	8.4	8.9	9.8	12.4	9.3	9.4	9.5	10.6	11.6
MADF	C	AN3	LAS(s)	PC	LDS(s)	C	AN3	LDS(s)	PC	LAS(s)
% DM	28.7	28.7	30.1	30.5	31.2	28.7	28.7	30.1	30.5	31.1
WSC	AN3	LAS(s)	LDS(s)	PC	C	AN3	LAS(s)	LDS(s)	PC	C
% DM	14.8	16.5	18.0	18.8	23.4	12.7	13.1	15.4	17.3	18.9
NO_3^- - N	PC	LAS(s)	C	LDS(s)	AN3	C	LDS(s)	PC	LAS(s)	AN3
% DM	0.005	0.005	0.006	0.006	0.011	0.006	0.006	0.006	0.007	0.027

* PC not determined

Treatments underlined by a common line are not significantly ($p < 0.05$) different by Tukey's W procedure.

Table 42 The Effect of Component 3 Treatments on the Ca, Mg and PTE Concentrations in Grass harvested in Cut 1, 1979

	Site A				Site B			
Ca	C	LDS(s)	LAS(s)	AN3	C	LAS(s)	LDS(s)	AN3
	0.32	0.34	0.36	0.40	0.21	0.21	0.23	0.25
% DM								
Mg	C	LDS(s)	LAS(s)	AN3	C	LAS(s)	LDS(s)	AN3
	0.11	0.11	0.12	0.12	0.09	0.10	0.10	0.12
Zn	C	LAS(s)	LDS(s)	AN3	C	LAS(s)	LDS(s)	AN3
	27.0	29.0	37.3	39.0	14.3	16.0	18.3	23.0
Cu	C	LDS(s)	AN3	LAS(s)	C	LAS(s)	LDS(s)	AN3
	6.0	6.0	6.5	7.3	3.8	5.3	5.5	5.8
mg kg^{-1} DM								
Ni	<3				<3			
Cd	<1				<1			
Cr	<3				<3			
Pb	<4				<4			

Treatment effects underlined by a common line are not significantly ($p < 0.05$) different by Tukey's W procedure.

Table 43 The Effect of Component 3 Treatments on the Ca, Mg and PTE Concentration in Grass harvested in Cut 1, 1980

	Site A					Site B				
Ca	C	LAS(s)	LDS(s)	PC	AN3	LAS(s)	C	PC	LDS(s)	AN3
	0.27	0.27	0.28	0.29	0.35	0.17	0.18	0.19	0.22	0.23
Mg	C	PC	LDS(s)	LAS(s)	AN3	C	PC	LDS(s)	LAS(s)	AN3
	0.12	0.12	0.13	0.14	0.14	0.12	0.16	0.16	0.17	0.17
Zn	C	PC	LDS(s)	LAS(s)	AN3	C	LAS(s)	AN3	PC	LDS(s)
	20.0	23.8	26.0	26.3	33.5	19.8	22.8	23.0	23.2	23.3
Cu	C	AN3	LAS(s)	LDS(s)	PC	C	AN3	LDS(s)	LAS(s)	PC
	4.8	5.0	5.5	5.8	7.0	4.5	5.3	5.5	5.5	6.8
Ni	C	PC	AN3	LDS(s)	LAS(s)	AN3	PC	C	LAS(s)	LDS(s)
	———	<1	———	3.5	4.0	——	<1 ——	3.8	4.3	4.5
Cd			<1					<1		
Cr			<3					<3		
Pb			<4					<4		

Treatment effects underlined by a common line are significantly ($p < 0.05$) different by Tukey's W procedure.

CP ($^1/E_N$), MADF and WSC results (Table 41) were plotted against N yield to determine whether the effect of the Component 3 treatment could be accounted for by the amount of available N supplied by end treatments (Figs 36, 37, 40, 41, 42 and 43). This was considered to be so although the selective winterkill of grass at Site A affected the response to AN (p 64). The absence of an effect of the Component 3 treatments on the NO_3^-- N, Ca and Mg concentrations in the grass in the first cut of the year (Table 41 to 43) has been noted and discussed in 6.1.

The possible increase in the concentration of Ni in the grass receiving the LDS s and LAS s treatments in 1980 is unlikely to have been due to an effect of the sludge N as there was no similar increase due to the AN3 treatment. However, it is also unlikely that the increase was due to the foliar retention of sludge solids as there were no marked increases in the concentration of Zn and Cu, elements present in the sludge in much larger amounts (Table 7). As the concentration of Ni remained within the range normally found in plant tissue, the increase may have been due to an environmental interaction.

These results suggest that the application of a single, large amount of liquid or solid sludge similar to those used in this trial would have the same effect upon the quality of grass cut at the silage stage as an inorganic N fertilizer supplying the same amount of available N. The concentration of WSC in all grass cut in early June in this trial was sufficient to permit ensiling without additives. This may not be so if sludge is applied to other grass species, if another management scheme is adopted or if environmental conditions are markedly different to those which were encountered during this field trial. The concentration of CP, Ca and Mg in all grass harvested in the first cut tended to be lower than recommended for good dairy cow nutrition (MAFF, 1975, Osbourne, 1980).

6.3 Summary and conclusion

The application of N tended to increase the concentration of CP NO_3^-- N and PTE's in the grass but to decrease the concentration of WSC. Both increases and decreases in the concentration of MADF were observed following the application of N. The concentration of Ca and Mg were little affected by the application of N.

The effect of the sludges on the concentration of CP, MADF, WSC, NO_3^-- N, Ca and Mg in the grass could be accounted for by the activity of the sludge N. The concentration of PTE's in the grass receiving the LAS was similar to that in the grass receiving AN whereas the grass receiving the LDS often had a concentration of PTE's above that in the AN treated grass. This was attributed to the foliar retention of LDS solids. Marked differences were noted between the maximum foliar retention capacity for solids from sludges of different types and solids contents.

The effect of the application of a large amount of LDS, LAS or PC on the quality of June cut silage could also be accounted for by the supply of available sludge N. The grass contained sufficient WSC to enable ensiling without additives but insufficient CP, Ca and Mg for adequate dairy cow nutrition.

CHAPTER 7

THE EFFECT OF THE USE OF SLUDGES AS N FERTILIZERS ON THE SOIL QUALITY

The purpose of the examination of the effects of selected treatments on certain aspects of soil quality was to assess the residual effects (good and bad) of the use of the sludges as N fertilizers.

7.1 Organic matter

7.1.1 Results

The estimates of the organic matter in soil samples from Site B were very high, probably due to the loss of structural water associated with the clay. Consequently the Site B results were not considered reliable.

The organic matter content of the soil under the C, PC, LDS3, LAS3 and AN3 treatments at Site A is given in Table 44. The results were analysed by a two-way analysis of variance (treatment x block) and the significance of the differences between individual treatment effects determined by Tukey's W procedure.

Table 44 The Effect of C, PC, LDS3, LAS3 and AN3 Treatments on the Concentration of Organic Matter in the Soil at Site A

Soil Organic Matter g dry weight kg^{-1} organic matter free soil					SIGN
Treatment					
C	PC	LDS3	LAS3	AN3	
53.8a	61.6b	62.4b	59.5ab	57.5ab	**

Treatments bearing the same letter are not significantly ($p < 0.005$) different.

The effects of the treatments were small in comparison with the background (C) level. The sludge and AN treatments increased the soil organic matter content above that of the control (C) although only the LDS3 and PC treatments increased it significantly ($p < 0.05$)

7.1.2 Discussion

The increase in the soil organic matter following the application of the AN3 treatment (although not significant, $p > 0.05$) was probably due to an increase in the below ground DM production of the grass. The significant ($p < 0.05$) increase in the soil organic matter following the application of the LDS3 and PC treatments and the not significant ($p > 0.05$) increase following the application of the LAS3 treatment were probably due to the combined effect of an increase in the below ground DM production of the grass in response to the sludge N, undecomposed sludge organic matter and organic matter of microbial origin created during the decomposition of the sludge.

The size of the increase in the soil organic matter was small in comparison with the amount already present in the soil and it is unlikely that agriculturally important changes in the physical properties of the soil occurred. As the soil organic matter content at Site B was greater than at Site A, it is likely that the effect of the sludge organic matter was even smaller at this site. Due to the short duration of the trial it is not possible to determine whether a substantial alteration in the physical properties of the soil would have occurred had the sludges been applied continuously at the same rate over a long period (20 to 30 years). The substantial loss of sludge organic matter during the field trial suggests this would not have been so.

7.2 Lime requirement

7.2.1 Results

The cumulative (1978 to 1980) lime requirement of soils under plots receiving treatments C, PC, LDS3, LAS3 and AN3 was calculated from the soil samples taken throughout the trial (Table 45). The results were analysed by two-way analysis of variance (treatments x blocks) at each site and the significance of differences between individual treatments determined by Tukey's W procedure.

Table 45 The Amount of Lime (as $CaCO_3$) required to maintain the Soil under Plots receiving Treatments C, PC, LDS3, LAS3 and AN3 at pH 6.0

Site	Lime Requirement t $CaCO_3$ ha^{-1}					SIGN
	C	PC	LDS3	LAS3	AN3	
A	0.40ab	-1.90a	0.50ab	-0.95ab	2.85b	***
B	0.85	1.90	1.20	0.20	3.15	NS

Treatments bearing the same letter are not significantly ($p < 0.05$) different.

The background variability of the data was very high at both sites. The lime requirement of soils receiving the AN3 treatment was greater than that of soils receiving the sludges at both sites although the difference in effect was only significant ($p < 0.05$) between the AN3 and PC treatments at Site A. The relationship between the treatment effects on the lime requirement was AN3 > LDS3 > C > LAS3 at both sites whilst the effect of the PC treatment varied between sites. The PC and LAS3 treatments caused a non-significant ($p > 0.05$) decrease in the lime requirement of the soil at Site A (ie an increase in soil pH).

7.2.2 Discussion

The high background variability of these results was probably due to a combination of sampling error, error in the determination of the soil pH and error associated with the calculation of the lime requirement from this pH (p 55).

The increase in the lime requirement due to the application of the AN3 treatment although not significant ($p > 0.05$) at either site was probably due mainly to the acidifying action of the NH_4^+- N of the AN. This acidifying action has been noted by previous authors (p 31). The lower lime requirement of soil receiving the sludge treatments although not significant ($p > 0.05$) except for soil receiving PC at Site A was probably due to the lower supply of NH_4^+- N (as NH_4^+- N or mineralizable organic N) plus the addition of sludge Ca.

The effect of the treatments on the lime requirement increased in the order LAS3 < LDS3 < AN3 at both sites suggesting that the action of these treatments on the lime requirement was similar on both soil types although the ultimate effects differed due to the greater increase in lime requirement at Site B, independent of the sludge and AN treatment effects. It is unclear why the action of the PC treatment differed between the sites, relative to the other treatment effects.

The decrease in the lime requirement of the soil receiving the LAS3 and PC treatments at Site A although not significant ($p > 0.05$) suggests that repeated applications of these sludges to soils with a low buffering capacity may lead to an increase in pH above that recommended for grassland (pH 6.0). This would be undesirable as lowered concentrations of some elements in the grass may lead to a mineral deficiency in the livestock.

7.3 Extractable phosphate

7.3.1 Results

The soil P extractable from plots receiving the C, PC, LDS3, LAS3 and AN3 treatments is given in Table 46. The results were analysed by a two-way analysis of variance for each site and the significance of differences between individual treatment effects determined by Tukey's W procedure.

Table 46 The Effect of Treatments C, PC, LDS3, LAS3 and AN3 on the Amount of P extractable from the Soil at the End of the Trial

Site	Extractable Soil P mg kg^{-1} dry soil					SIGN
	Treatment					
	C	PC	LDS3	LAS3	AN3	
A	49a	71bc	87c	72c	52ab	***
B	81	71	92	90	72	NS

Treatment effects bearing the same letter are not significantly ($p < 0.05$) different.

The sludge treatments significantly ($p < 0.05$) increased the extractable soil P above that of the control (C) plots at Site A but not at Site B. The amount of P extractable from plots receiving the AN3 treatment was similar to that extractable from plots receiving the C treatment at both sites.

7.3.2 Discussion

The results indicate that the conventional (MAFF) P maintenance program was successful in maintaining the soil P reserve at both sites. The accumulation of extractable P on plots receiving the sludge treatments at Site A indicates that the supply of extractable sludge P exceeded the amount of P removed in grass harvested. The absence of a similar effect at Site B can be accounted for by the greater DM yields (and therefore probably P yields) taken from this site.

These results suggest that on many soils the amount of P supplied by sludges will equal or exceed that removed in grass crops. If the P removed in grass crops is returned in animal manure, a substantial increase in the concentration of extractable P in the soil may be expected. Given the strength with which P is bound in most soils, such an accumulation is unlikely to be problematic unless surface runoff to a watercourse occurs.

7.4 Concentration of potentially toxic elements

7.4.1 Results

The concentration of PTE's in the soil of plots receiving the C, PC, LDS3, LAS3 and AN3 treatments is given in Table 47 The Cd results could not be analysed by two-way analysis of variance due to the presence of values below the detection limit. The Cd results are given in Table 47 according to the rules given on p 98.

The application of the sludges increased the concentration of Zn in the soil at both sites although the increase was only significant

($p < 0.05$) in soil receiving the LDS3 treatment at Site A. The concentration of Cu in the soil was also increased at both sites but the increase was only significant ($p < 0.05$) in soil receiving the PC treatment. Both the PC and LDS3 treatments appeared to increase the concentration of Cd in the soil whilst the LAS had no detectable effect. The concentration of Ni, Cr and Pb was not greatly affected by sludge applications. The AN3 treatment had little effect on the soil PTE concentrations at either site.

Table 47 The Effect of Treatments C, PC, LDS3, LAS3 and AN3 on the Concentration of selected PTE's in the Soil at the end of the Trial

Element	Site	Concentration of PTE's mg kg^{-1} dry soil					SIGN
		Treatment					
		C	PC	LDS3	LAS3	AN3	
Zn	A	39a	45ab	57b	42ab	36a	*
	B	57	70	68	54	56	NS
Cu	A	8.3ab	13.3c	12.8bc	12.5bc	7.5a	*
	B	17.5a	25.8b	20.5ab	19.0ab	18.0a	*
Ni	A	6.0	6.8	6.3	7.0	5.5	NS
	B	18.3	17.3	16.5	16.3	20.3	NS
Cd	A	0.25	0.38	0.38	0.25	0.25	ND
	B	0.25	0.31	0.44	0.25	0.25	ND
Cr	A	8.0	6.8	9.5	8.0	8.3	NS
	B	21.0	21.0	21.0	18.0	19.8	NS
Pb	A	25.5	27.0	32.0	27.5	25.5	NS
	B	48.5	56.5	47.0	46.0	52.0	NS

Treatment effects bearing the same letter within the same row are not significantly ($p < 0.05$) different.

ND = not determined.

7.4.2 Discussion

The application of the sludges did not elevate the concentration of any of the PTE's above the range which is normally found in soils (compare Table 47 with Table 6). The largest percentage increase in PTE concentration was probably in that of the Cd although the reliability of these results could not be tested. The increases in soil PTE concentrations due to the application of the sludges broadly reflect the differences in the amount of PTE applied in each type (Appendix 7) although increases in the concentrations of Pb and Cr were lower than might have been expected.

The fate of Zn and Cu applied to the soil in the sludges was investigated by drawing up a balance sheet using sludge, plant and soil analyses (Table 48). These elements were selected because the concentrations in the grass were sufficiently high to permit accurate analyses. Table 48 shows large discrepancies between the amount of sludge Zn and Cu applied and the amount recovered in the grass and soil. Leaching of Cu and Zn from the soil is unlikely given the immobility of these elements in the soil (p 28) and the source of the discrepancies probably lies in the estimation of the amount of Zn and Cu in the soil. This makes the balance of little value in examining the movement of these elements within the plant/soil system. Nevertheless the results in Table 48 agree with the conclusions of Doyle et al. (1978) that little of the PTE's applied in sludges is recovered in plant crops. This is despite the probable inclusion of sludge solids in the grass harvested (p 100).

Table 48 The Fate of Zn and Cu applied to the Soil in Sludge

Site		Zn g ha^{-1}		
		Treatment		
		LAS3	LDS3	PC
A	Zn applied	7455	24143	11656
	Recovered in grass	413	491	ND
	Recovered in soil	2920	15500	5130
	Discrepancy*	4122	8152	ND
B	Zn applied	7118	24313	11593
	Recovered in grass	364	367	ND
	Recovered in soil	2351	7481	9263
	Discrepancy*	4403	16465	ND

Site		Cu g ha^{-1}		
		Treatment		
		LAS3	LDS3	PC
A	Cu applied	6113	7824	6061
	Recovered in grass	117	89	ND
	Recovered in soil	3761	4027	4469
	Discrepancy*	2235	3708	ND
B	Cu applied	5882	7878	6029
	Recovered in grass	113	91	ND
	Recovered in soil	-713	2138	6056
	Discrepancy*	6482	5649	ND

* applied - (recovered in grass + recovered in soil)

ND = not determined.

7.5 Earthworm population

7.5.1 Results

The number and weight of earthworms extracted from plots receiving treatments C, PC, LDS3, LAS3 and AN3 at the end of the trial are given in Table 49 and 50 respectively. The results were $\sqrt{x + 1}$ transformed prior to a two-way analysis of variance as earthworm results tend to follow a Poisson distribution.

A greater number and weight of L. terrestris and A. longa were extracted from Site B than from Site A whilst a similar number and weight of A. caliginosa gp. were extracted from both sites.

The application of AN had little effect on the number and weight of L. terrestris at Site A whereas it increased the number and weight (not significantly, $p > 0.05$) at Site B. The application of the sludges increased the number and weight of L. terristris at both sites although these effects were also not significant ($p > 0.05$).

The sludge and AN treatments had little effect on the number or weight of A. longa at Site A whilst both the AN3 and the sludge treatments increased (not significantly, $p > 0.05$) the number and weight at Site B.

The application of AN increased the number and weight of A. caliginosa gp. at both sites although the increase was not significant ($p > 0.05$) at either. The applications of the sludges had little effect on the number and weight of the A. caliginosa gp. at Site A. The LDS3 and LAS3 decreased both the number and weight of this group non-significantly ($p > 0.05$) at Site B although the difference between the AN3 and the LDS3 and LAS3 treatment effects was significant ($p < 0.05$).

Both the applications of sludges and AN increased the total weight of earthworms in both soils although the increases were not significant ($p > 0.05$). The total number of earthworms extracted from Site A was increased though not significantly ($p > 0.05$) by the application of either the sludges or AN. At Site B the total number of earthworms extracted was raised by the PC, LDS3 and AN3 treatments but reduced by the LAS3 treatment. The effects were not significant ($p > 0.05$) although the number of earthworms extracted from the AN3 treated plots was significantly ($p < 0.05$) greater than those extracted from the LAS3 treated plots.

Table 49 The Number of Earthworms extracted at the End of the Trial from Plots receiving the C, PC, LDS3, LAS3 and AN3 Treatments

Species Group	No. Earthworms, individuals m^{-2}					SIGN
	Treatment					
	C	PC	LDS3	LAS3	AN3	
			Site A			
L. terristris	14	9	23	31	10	NS
A. longa	24	18	19	15	23	NS
A. caliginosa gp.	60	61	60	54	122	NS
Total	98	115	102	146	155	NS
			Site B			
L. terristris	40	42	47	42	54	NS
A. longa	30	45	52	33	42	NS
A. caliginosa gp.	71ab	84ab	49a	39a	111b	*
Total	141ab	171ab	148ab	114a	207b	*

Treatment effects bearing the same letter within a row are not significantly ($p < 0.05$) different.

Table 50 The Dry Weight of Earthworms extracted at the End of the Trial from Plots receiving the C, PC, LDS3, LAS3 and AN3 Treatments

Species Group	Dry Weight of Earthworms, g m^{-2}					SIGN
	Treatment					
	C	PC	LDS3	LAS3	AN3	
			Site A			
L. terrestris	3.6ab	6.2ab	10.0ab	11.7b	3.2a	*
A. longa	7.4	8.6	7.7	6.3	7.2	NS
A. caliginosa gp.	4.0	4.6	7.7	3.7	9.1	NS
Total	15.0	19.4	25.4	21.7	19.9	NS
			Site B			
L. terrestris	8.3	14.5	18.9	14.1	13.7	NS
A. longa	6.0	14.5	15.3	11.2	8.1	NS
A. caliginosa gp	7.1	7.0	5.6	6.3	9.8	NS
Total	21.4	33.7	40.0	31.6	31.6	NS

Treatment effects bearing the same letter within a row are not significantly ($p < 0.05$) different.

7.5.2 Discussion

The results of the extraction of earthworms from the plots receiving the various treatments must be considered with caution. The plot size and shape adopted in the field trial was designed to assess the effects of the treatments on the grass rather than on the earthworms. The plot size and guard strips may therefore not have been adequate to prevent the migration of earthworms from one plot to another.

The number of earthworms extracted from the soil at the two sites (Table 48) was below the range normally found in grassland soils (Edwards and Lofty, 1972). This probably reflects the difference between the efficiency of the formalin extraction method adopted in this trial and the formalin plus handsorting method used in previous investigations. A larger number of earthworms are normally found in sandy loam soils than in heavy clay soils (p 34) The reason for there having been a larger number of earthworms extracted at Site B in comparison with Site A may lie in an interaction between the extraction method and one or more differences in site characteristics.

The application of the AN and the sludges increased the DM production of the grass and probably increased the amount of organic matter reaching the soil. An increase in the supply of food may explain some of the possible increase in the weight and number of L. terrestris at Site A and both L. terrestris and A. longa at Site B following the sludge and AN treatments (Tables 49 and 50). The application of the LDS3, LAS3 and PC treatments also added about 12.9, 9.6 and 14.2 t dry weight organic matter respectively, much of which appears to have been biodegradable (p 107). This additional source of food may explain why the effect of the sludge treatments on the number and weight of L. terrestris and A. longa was probably greater than could be accounted for by the stimulation of grass growth by sludge N. The effects of the PC treatment may have been lower than those of the LDS3 and LAS3 despite the application of more organic matter. The low availability of the PC N (p 72) and the longer time between the last application of the sludge and the earthworm extraction may have been responsible for this apparent lack of effect.

Andersen (1979) commented upon the marked increase in the number and biomass of A. longa following applications of dried sludge. The results obtained in this trial suggest that the number and weight of both L. terrestris and A. longa may have been increased at Site B but that only L. terrestris may have been increased at Site A. As the effect of the AN3 treatment appeared to behave in a similar fashion, the action of the sludge N on grass production and an interaction with a site characteristic (possibly rooting depth) may have caused this apparent difference in the effect of the sludge on A. longa at the two sites. Andersen (1979) also found A. caliginosa and A. rosea to be suppressed by sludge applications. In this trial the sludge treatments had little effect on the number or weight of the A. caliginosa gp. extracted at Site A but there is some indication that the LDS3 and LAS3 treatments may have suppressed the number but not the weight of this group at Site B. The results are too variable and the composition of the A. caliginosa gp. too ill defined to permit an interpretation of this apparent effect.

The changes in the total earthworm population due to the application of the sludges and AN are unlikely to have had an important effect on soil properties. However, the increase in L. terrestris and A. longa populations may have increased the redistribution of PTE's down the soil profile.

7.6 Summary and conclusion

The PC, LAS3 and LDS3 treatments supplied 14.2, 9.6 and 12.9 t dry weight organic matter respectively over the $2\frac{1}{2}$ years, much of which appeared to have been decomposed by the end of the trial. The increase in soil organic matter at Site A and probably at Site B as a result of these additions was small in comparison with the amount of organic matter already present and unlikely to be of agricultural importance.

The applications of the sludges tended to reduce the soil lime requirement and the PC and LAS may have led to an increase in pH of the sandy soil. This suggests that the pH of soils of low buffering capacity receiving regular applications of PC and LAS should be monitored to ensure that it does not rise sufficiently to cause mineral deficiencies in livestock.

The supply of sludge P was more than sufficient to satisfy the maintenance P requirement of the soil and led to an increase in the extractable P in the soil. Under a farming system which returns much of the P removed in the crop in manure, the amount of extractable P in the soil could rise substantially.

The applications of the sludges tended to increase the concentration of PTE's in the soil although there were large discrepancies between the amount of PTE's applied and the amount recovered in soil and crops. The source of these discrepancies was thought to be experimental error. It is likely that about 2% of the sludge PTE's applied was recovered in the grass crop over the duration of the trial.

The sludge treatments tended to increase the number and weight of *L. terrestris* extractable from the sandy loam and of *L. terrestris* and *A. longa* from the clay soil. The number of *A. caliginosa* gp extractable from the sandy soil was little affected by the sludge applications whereas the number of this group extracted from the clay soil was probably depressed by the applications of LAS and LDS. The reason for this apparent depression was not determined. The effect of the sludge applications was probably not of agricultural importance although because it was not possible to determine whether the population had stabilized, the exact impact of these and any further applications could not be assessed.

CHAPTER 8

THE USE OF SLUDGES ON GRASS/CLOVER SWARDS

8.1 Introduction

In the absence of fertilizer N, the yield of a grass/clover sward is greater than that of a pure grass sward due to the fixation of atmospheric N in the clover root nodules. Measured as the amount of fertilizer N required to obtain the same DM yield from a pure grass sward, N fixation supplies between 40 and 220 kg N ha^{-1} yr^{-1} with a mean value of about 140 kg N ha^{-1} yr^{-1} (Brockman, 1974). Most lowland grass in the UK will give an economical yield response to fertilizer N to above 300 kg N ha^{-1} yr^{-1} (Morrison et al., 1980) so supplementary N must be applied to most grass/clover swards if the full DM yield potential is to be exploited.

The greatest shortfall in the herbage yield of a grass/clover sward normally occurs in the spring (Denehy and Morrison, 1979). The application of fertilizer N in early spring has been found to increase the spring DM yield of grass but depress the clover content of the sward. The net effect is an increase in spring herbage DM yield but a decrease in the mid-season herbage DM yield in comparison with the unfertilized sward. The depression of mid-season DM yield partly counteracts the spring increase so the response to N in the annual DM yield is small but positive.

Fertilizer N applied to a grass/clover sward is taken up predominantly by the grass (Walker et al., 1956). The subsequent increase in grass growth increases the competitive stress upon the clover resulting in a partial elimination of the clover from the sward (Ennik, 1970). The input of fertilizer N is offset by the loss of N fixation and the N yield of the sward is unaltered (Ennik, 1981).

Ennik (1970), using data from many sources, found the relationship between annual grass and annual clover DM yield to be inverse and linear over a wide range of grass and clover yields. This relationship was used by him to determine whether the effect of a treatment upon the yield of clover was dependent or independent of the grass response to N. The availability and rate of release of sludge N is lower than that of the commonly used inorganic N fertilizers (p 20). Sludges also contain other macronutrients, micronutrients, PTE's and water and are biologically active. Davies (1977) found clover to be more sensitive to the phytotoxic PTE's than grasses. The response of a grass/clover sward to the application of a sludge is therefore likely to differ from that obtained with inorganic N fertilizers.

Magdoff and Amadon (1980) conducted a two year trial with LAS on a 15 year old mixed species grass/clover sward. Sludge (0-411 kg N ha^{-1} yr^{-1}) and inorganic N (0-200 kg N ha^{-1} yr^{-1}) was applied after the first and second cut in each year. The mean DM yield response was about 23 and 16 kg DM kg^{-1} N for the inorganic N and sludge respectively. The individual contribution of the grasses and clovers was not given but the low control yield suggests that the clover was a small or inactive constituent of the sward.

Geering and Kunzli (1967) conducted a twelve year, two part field trial with LDS and a ground, air-dried sludge on an old, mixed species sward. The sward was cut three or four times a year in part I and II respectively. LDS (average 240 kg N ha^{-1} yr^{-1}) and inorganic N (average 87 kg N ha^{-1} yr^{-1}) were applied in split doses to each growth period. The dried sludge (average 143 kg N ha^{-1} yr^{-1}) was applied in the autumn. Most of the DM yield increases obtained could be attributed to the supply of P. The marginal response to the inorganic N, LDS and air-dried sludge was 11.0, 2.2 and 0 kg DM kg^{-1} N, averaged over the twelve years. Neither the inorganic N plus P, LDS nor the dried sludge increased the yield of N above that of the control plus P treatment. According to the work of Ennik (1981) this would suggest that the sward responded to the sludge N only, once the P deficiency was relieved.

Coker (1966 a) examined the response of a mixed species grass/clover sward to spring N applied as inorganic N or LDS. Only the details of the first cut (in June) were recorded and the contribution of clover was not measured. The DM yield response to the sludge was similar to that from the inorganic N. A pasture analysis undertaken 32 months after resowing and following two spring applications of N found the sludge plots to support a larger white clover population than the inorganic N plots. This suggested some advantage may be gained by using LDS in preference to inorganic N for the spring fertilization of grass/clover swards.

The work of Geering and Kunzli (1967) clearly showed that a response to a sludge constituent other than N can occur. The yield response to sludge N differed considerably between the three papers cited. Given the difference in experimental conditions, the variation in sludge type and lack of information on the individual yield of grass and clover, it is not possible to determine why the DM yield response differed or whether factors other than the response to N were involved. The following experiment was therefore designed to determine the response of a grass/clover sward to different types of sludge and to investigate the possibility that sludge constituents other than N and P could affect the performance of the sward.

It was assumed that the results of Geering and Kunzli (1967) proved that a DM yield response to sludge P may occur where P is deficient. Consequently P was supplied to all treatments in the following experiment. The K content of sludge is so low that its activity does not warrant consideration (p 5) and it too was supplied to all treatments.

A single application of sludge or inorganic N was selected, timed to increase spring herbage DM yield. The N sources were applied at a medium and high rate where possible to investigate level and level x source effects. The choice of sludge types has been explained on p 39. The experiment was conducted in pots due to limited time and space. The workload imposed by the main field trial meant only the DM yields of the grass and clover fractions could be determined.

8.2 Materials

8.2.1 Site characteristics

The experiment was conducted at the main field trial site A. The Site A soil was used in the experiment because it was easy to handle and was known to support a natural white clover population. A full description of this soil is given in Table 9. The meteorological data for this site can be found in Figs 4 to 6.

8.2.2 Grass and clover

A danger inherent in the use of pots to contain the grass/clover sward is the possible extinction of the clover following the application of N. Consequently an 'N tolerant' wild white clover (*Trifolium repens* cv Blanca) was selected. The companion grass (*Lolium perenne* cv S23) was chosen for its persistence and because it is a recognised standard.

8.2.3 Sludges and fertilizers

The sludges used in this experiment were LDS, LAS and a PC. The details of the origin, collection and analysis of the sludge are given in 3.2.1 . The inorganic fertilizers used were chosen to represent those in common agricultural use. The details of the fertilizers are given on p 41.

8.3 Experimental method

8.3.1 Establishment of the sward

In December 1978 soil was collected for the top 30 cm at site A and the coarse stones and plant material were removed by hand sorting. The pH and lime requirement were determined and hydrated lime added to bring the pH to between 6.0 and 6.5. Superphosphate (equivalent to 200 kg P_2O_5 ha^{-1}) and KCl (equivalent to 120 kg K_2O ha^{-1}) were mixed into the soil.

Forty plastic pots (30 cm dia) were filled to a depth of 23 cm with the prepared soil. The pots were sown with Lolium perenne cv S23 (equivalent to 18 kg seed ha^{-1}) and Trifolium repens cv Blanca (equivalent to 2.25 kg seed ha^{-1}). Extra clover was grown in a seed tray to supply transplants where establishment was poor. The sward was grown in a glasshouse (18 to 24°C, 16 hour daylength) until mid January. The plant density was adjusted by pricking out or transplanting to about 71 grass plants and 21 clover plants per pot, prior to the transfer of pots to a cooler glasshouse (8 to 16°C, natural daylength). In late February the pots were moved to a cold frame (-1 to 20°C, natural daylength).

On 22 March 1979 the pots were taken by lorry to site A and were dug in to sward level, adjacent to the main field trial.

8.3.2 Experimental design

A randomised block design was selected with five blocks lying along a temperature gradient in the glasshouses and down the slope at site A. The eight treatments applied are described in Table 51. The treatments were randomised within the blocks, as shown in Fig 45. The rates of application were chosen to be equivalent to 75 and 150 kg N ha^{-1} at the medium and high rates respectively. Due to the low fertilizer efficiency expected from the PC, a higher application rate was considered necessary in order to obtain a detectable response. Only the medium level of this treatment was applied since a high rate of application would have smothered the sward.

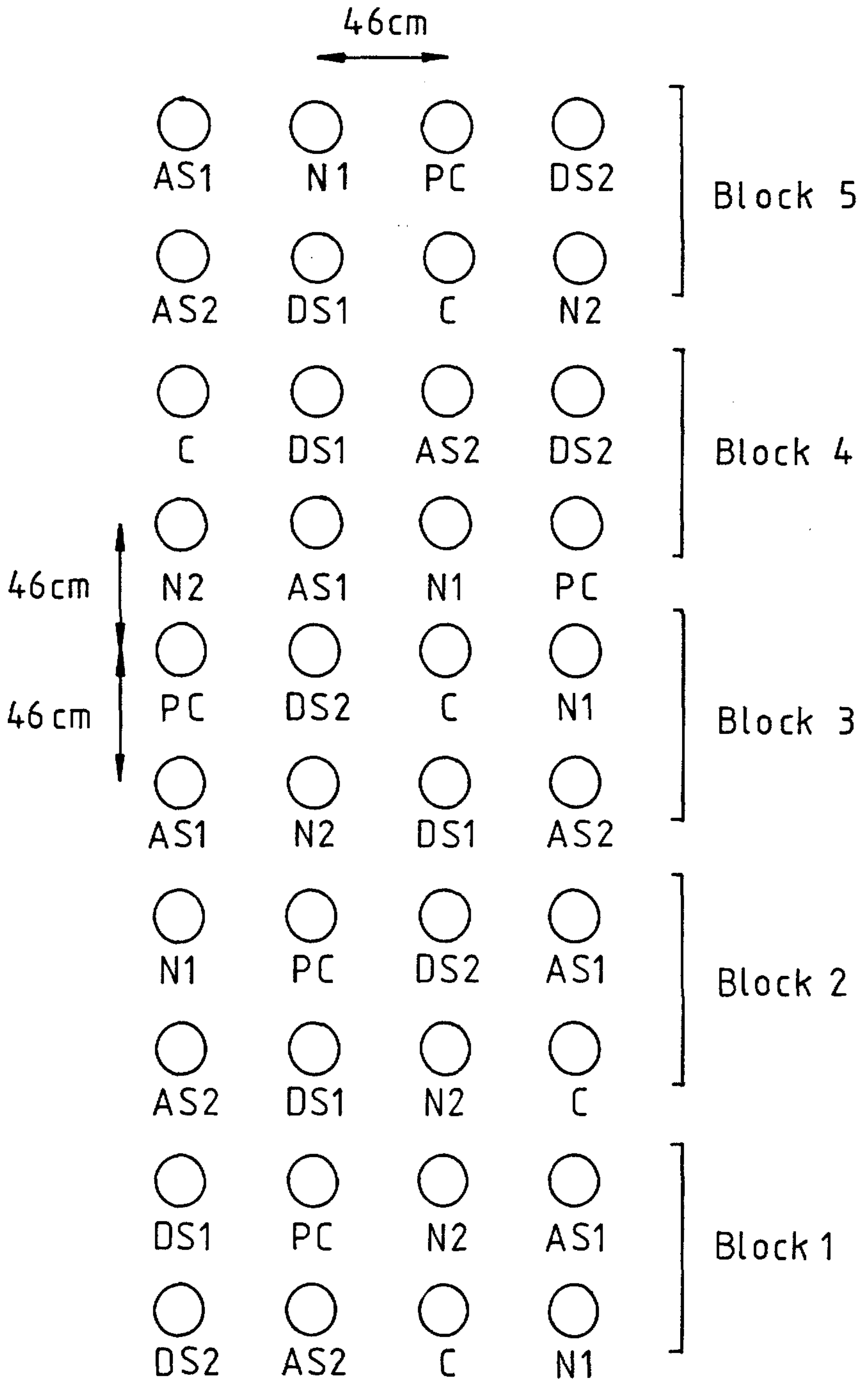


Fig 45 The layout of the grass/clover pot experiment.

Table 51 Treatments applied in the Grass/ Clover Experiment

Nitrogen Source	Application Rate g N m^{-2} yr^{-1}	Treatment Symbol
AN	7.5	N1
	15.0	N2
LDS	7.5	DS1
	15.0	DS2
LAS	7.5	AS1
	15.0	AS2
PC	36.0	PCS
Control	0	C

8.3.4 Treatment application and harvesting

The AN, LDS and LAS were applied in late March in both 1979 and 1980. The PC was applied once in December 1979 (Table 52).

The AN was weighed in the laboratory and taken to the site in sealed test tubes, from which it was broadcast directly to the pots. The liquid sludges were taken to the site in 10 l plastic sample containers. The contents were thoroughly shaken and sub-samples (about 400 ml) removed. The required volume of sludge was poured into a measuring cylinder (250 ml) then applied directly to the pots. The PC was weighed in the laboratory then chopped to about 1 cm^3. The chopped cake was taken to the site in sealed plastic bags and spread by hand.

The herbage was cut six times a year (Table 52). This regime favoured the persistence of the white clover and conveniently enabled two harvests to be allocated to the spring, mid and late season growth periods. The grass surrounding the pots was cut at each cutting date. The herbage was cut to a height of about 1 cm with a pair of one-handed shears. All the herbage from the pot was placed in plastic bags, sealed and returned to the laboratory for hand sorting into grass and clover

Table 52 Dates of Applications and Cuts

Year	Date of Application	Date of Cut					
	AN, LDS, LAS	1	2	3	4	5	6
1979	23/3	17/5	15/6	6/7	3/8	1/9	13/10
1980	3/4	16/5	16/6	3/7	31/7	22/8	3/10
	PC						
	17/12/79						

fractions. There was insufficient dead material to warrant subdivision into live and dead. The occurrence of unsown species was insufficient to warrant investigation and these were discarded on site. Samples which could not be processed immediately were stored at 1°C (up to ten days) or -18°C (in excess of ten days).

8.3.5 Maintenance of soil nutrient status

A single application of superphosphate (equivalent to 70 kg P_2O_5 ha^{-1}) was made in March 1980 to supplement that applied prior to establishment. K fertilizer (equivalent to 60 kg K_2O ha^{-1} yr^{-1}) was applied in six equally split amounts after each cut in 1979 and 1980. One dressing of Mg fertilizer (equivalent to 60 kg Mg ha^{-1}) was made in April 1980. The pH of each pot was determined after the last cut in 1979. No liming was required.

8.4 Analysis

8.4.1 Chemical analysis

The grass and clover fractions of each sample were dried at 100°C overnight then weighed.

The techniques used to analyse the soil have been given in 3.3.11 .

8.4.2 Statistical analysis

The data from each cut and year were statistically analysed on the GENSTAT Version 4 Mk 1 package at Severn Trent Water Authority Headquarters, Birmingham. The analysis was in two parts:-

1) A two-way analysis of variance of treatment x blocks for the grass, clover and whole sward yield to obtain the error mean square. The significance of the PC treatment was determined using Tukey's W procedure. The coefficient of variation of the DM yields was calculated as an index of the variability of the data.

2) A breakdown of the AN, LDS and LAS treatment effects as described in Table 53.

Table 53 Differences tested by Analysis of Variance

Symbol	Difference Tested
NRESP	Control v N treatments (source and levels pooled)
SCE*	AN v LDS v LAS (levels pooled)
LEV	N level 1 v N level 2 (sources pooled)
SCE x LEV	Source x level interaction

* The difference between the sources were tested using Tukey's W procedure whenever the SCE test was significant.

The relationship between the total clover and total grass yield for the AN was estimated by a regression, using the C, N1 and N3 results. The significance of the deviations of the sludge treatments from this relationship was tested using the student's t test.

8.5 Results

The variation in the clover DM yield results (CV 24.8% to 56.4%) was greater than that of the grass DM yield results (CV 9.2% to 21.6%) and both were greater than that of the whole sward DM yield results (CV 9.0% to 19.3%). There was no noticable pattern in the individual CV's either within or between years.

8.5.1 Grass yield

The annual DM yield of grass (Fig 46) from the control treatment was similar in both years although the seasonal distribution of DM yield was more even in 1980 than in 1979 (Figs 47 and 48)

The PC treatment significantly ($p < 0.05$) increased the annual DM yield of grass in comparison with the control (Table 54) but not the DM yields of the individual cuts. The breakdown of the other treatment effects is given in Tables 55 and 56.

The response to spring N was larger in cut 1 and 2 and smaller in subsequent cuts in 1979 than in 1980 (Figs 47 and 48). The response in the annual grass DM yield was similar in each year. In both years the response to inorganic N was greater than to the sludges in cut 1 and 2 and in the annual grass yield (Table 56). The residual effect of the LAS was greater than that of the AN in cuts 4, 5 and 6 in 1980 and also greater than that of the LDS in cut 2 in 1979 and cuts 3 and 4 in 1980.

8.5.2 Clover yield

The yield of clover in each cut in 1979 and 1980 is given in Fig 47 and Fig 48.

The annual yield of clover (Fig 46) from the control treatment was similar in both years. In 1979 the yield of clover was low in cuts 1 and 2 (Fig 47) then progressively increased in cuts 3 to 6 whilst in 1980 (Fig 48) the yield was more evenly distributed over the season.

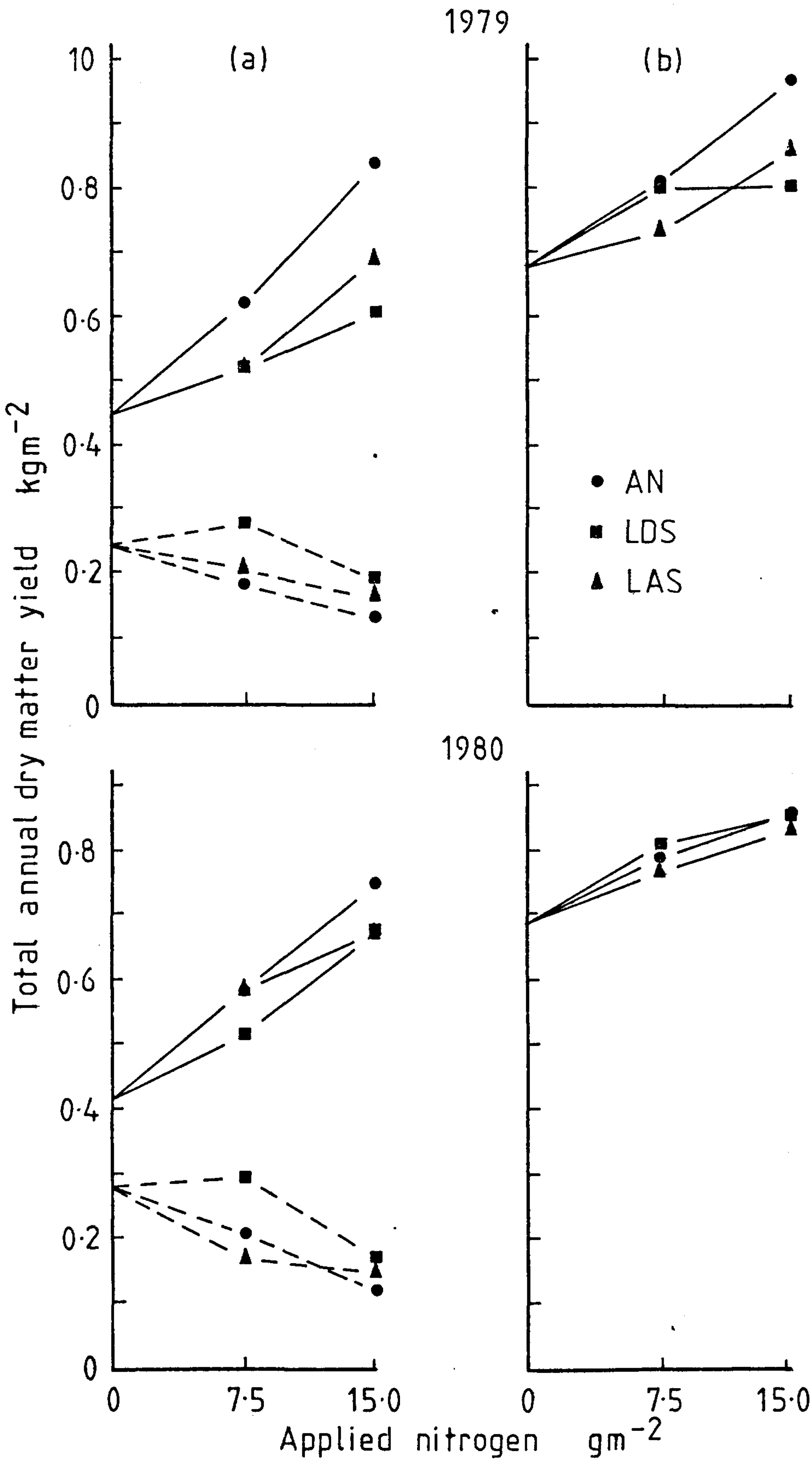


Fig 46 The relationship between the applied nitrogen and (a) the yield of grass (——) and clover (- - -) (b) the whole sward yield in 1979 and 1980.

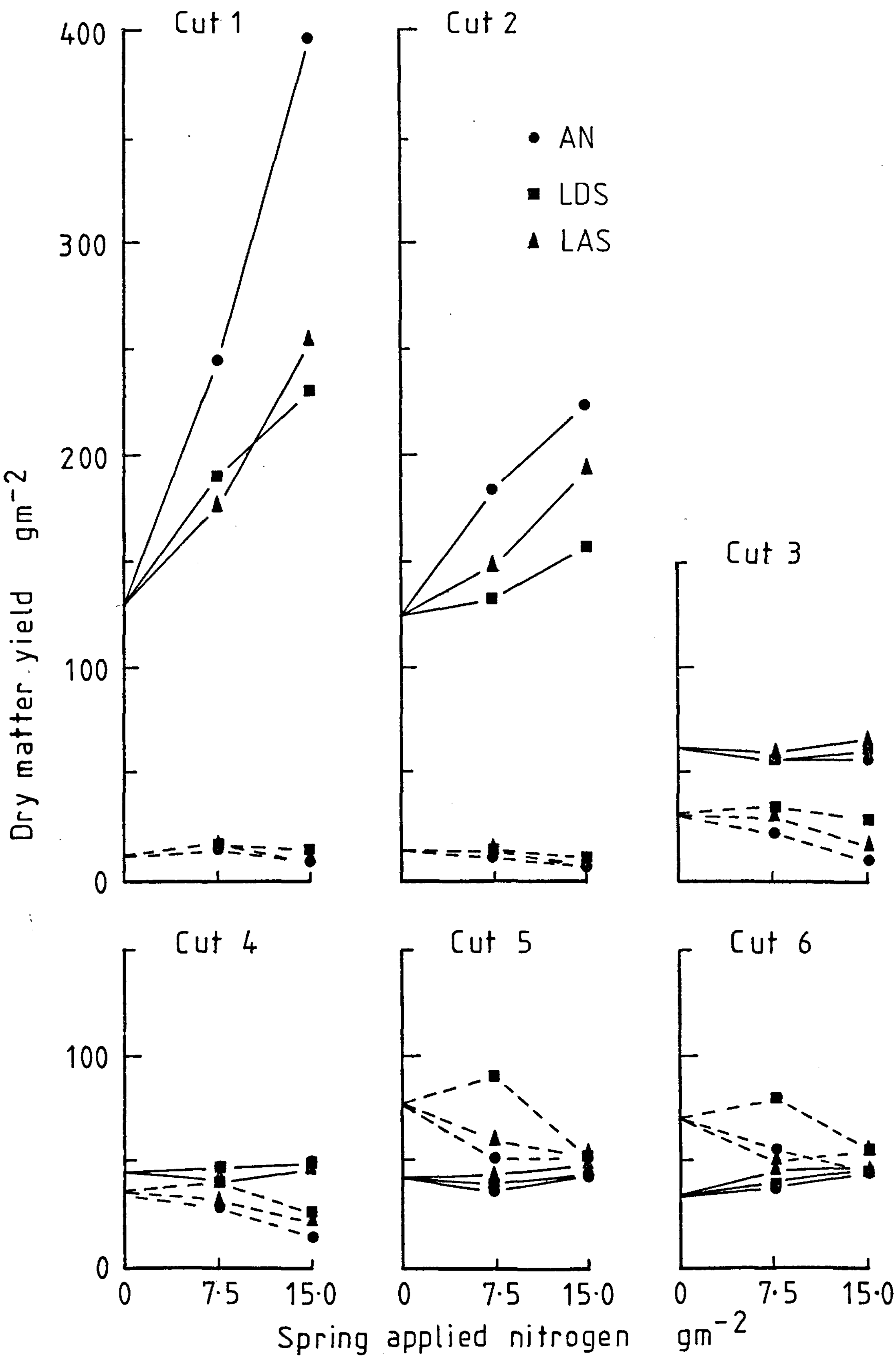


Fig 47 The relationship between spring applied nitrogen and the yield of grass (——) and clover (- - -) at each cut in 1979.

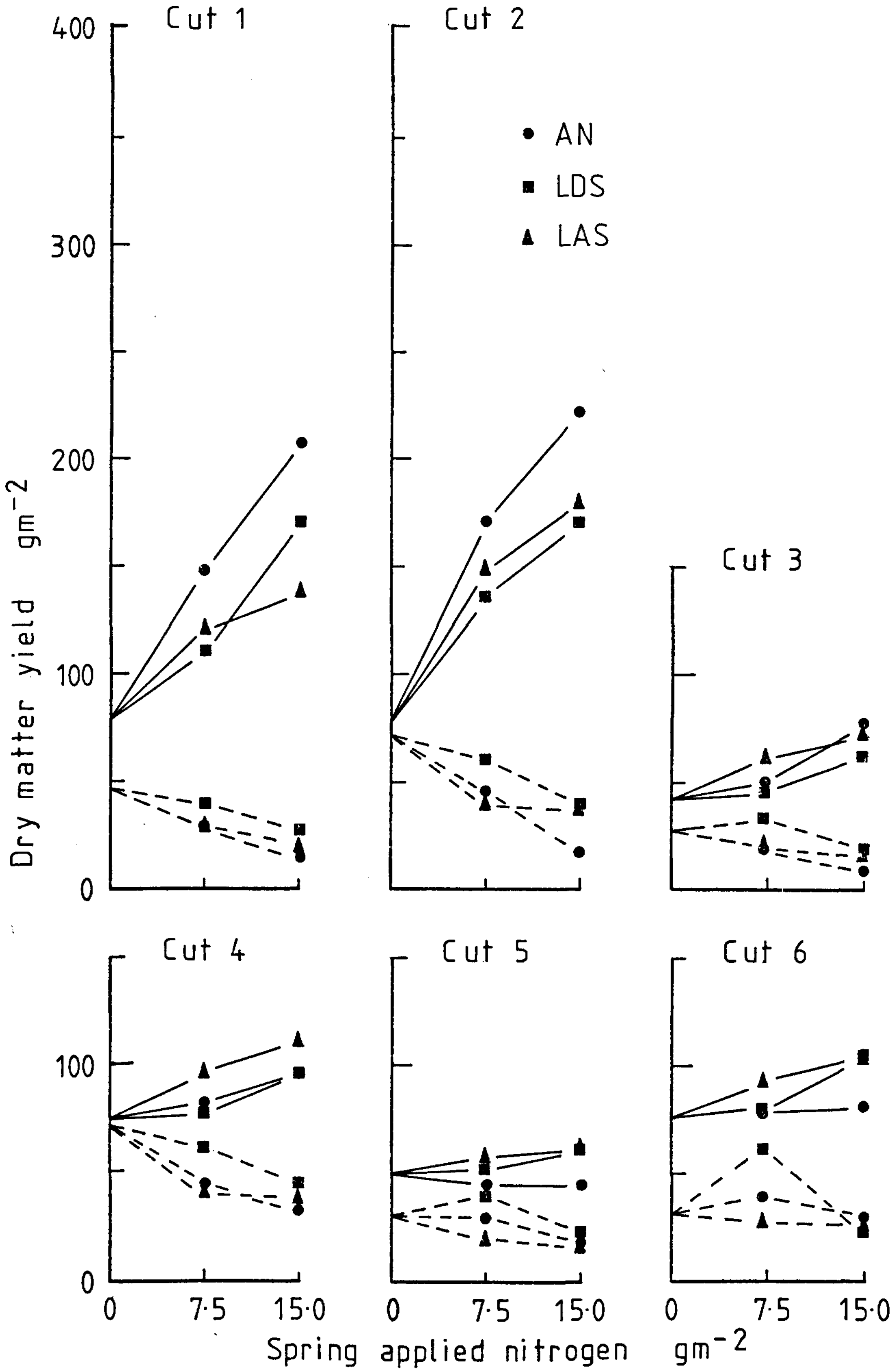


Fig 48 The relationship between spring applied nitrogen and the yield of grass (——) and clover (---) at each cut in 1980.

Table 54 Increase in the Yield of Grass due to PC Treatment

Year		Cut No						Total
		1	2	3	4	5	6	
1980	Yield Increase gm^{-2}	49	18	5	12	5	18	108
	Sign.	NS	NS	NS	NS	NS	NS	*

Table 55 Breakdown of AN, LAS and LDS Treatment Effects on the DM Yields of Grass

Test	Cut No													
	1979							1980						
	1	2	3	4	5	6	Tot.	1	2	3	4	5	6	Tot.
N RESP	***	***	NS	NS	NS	*	***	***	***	*	***	NS	*	***
SCE	***	***	NS	NS	NS	NS	***	**	***	*	***	***	**	*
LEV	***	***	NS	NS	**	*	***	***	***	***	***	NS	*	***
SCE x LEV	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

For key to tests, see p 126

Table 56 The Significance of the Effect of the Source of Spring N on the DM Yield of Grass

	Cut	Source		
		Increasing Yield →		
1979				
	1	LDS	LAS	AN
	2	LDS	LAS	AN
Total		LDS	LAS	AN
1980				
	1	LAS	LDS	AN
	2	LDS	LAS	AN
	3	LDS	AN	LAS
	4	DS	AN	LAS
	5	AN	LDS	LAS
	6	AN	LDS	LAS
Total		LDS	LAS	AN

Treatments not underlined by a common line are significantly different ($p < 0.05$) by Tukey's W procedure. Cuts in which the differences between sources were not significant ($p > 0.05$) have been omitted.

There was no significant ($p < 0.05$) difference between the PC and control treatments. The breakdown of the other treatment effects is given in Tables 57 and 58. The overall effect of N and level of application was not consistent, partly due to the variability of the data but also due to difference between sources and a possible departure from a linear response (Fig 48). Where differences between sources were significant ($p < 0.05$), the AN depressed clover yields to a greater extent than did the LDS (Table 58).

8.5.3 Whole sward yield

The yield of the whole sward in 1979 and 1980 is given in Fig 49 and 50. The breakdown of the treatment effects on the yield of the whole sward is given in Table 59.

The annual yield of herbage from the control plots was similar in both years (Fig 46). The difference in the distribution of the yield of grass and clover over the seasons was counteractive such that the distribution of the yield of the whole sward was more even than that of its constituents (Figs 47 and 48). The significance of the treatment effects on the yield of the whole sward is given in Table 60. The PC treatment did not significantly ($p < 0.05$) increase the yield of the whole sward above that of the control in any cut or in the annual yield.

The breakdown of treatment effects in Table 59 shows that there was a positive response to N and level of application in cuts 1 and 2 of both years but no overall depression of mid or late season yields, due to differences between sources (Figs 49 and 50). The AN elevated spring yields and depressed mid and late season yields to a greater extent than did the LDS in 1979 and the LAS in 1980 (Table 60). There was no significant difference ($p > 0.05$) between the yields from the sludge treatments except in cut 2, 1979. There was a significant ($p < 0.01$) source x level interaction between the inorganic N and LDS in cut 1 and in the annual yield ($p < 0.05$) in 1979.

Table 57 Breakdown of AN, LAS and LDS Treatment Effects on the Yield of Clover

Test	Cut No													
	1979							1980						
	1	2	3	4	5	6	TOT	1	2	3	4	5	6	TOT
N RESP	NS	*	NS	NS	*	*	*	***	**	NS	**	NS	NS	**
SCE	NS	NS	*	NS	**	NS	**	*	NS	*	NS	NS	NS	**
LEV	NS	*	*	**	*	NS	**	**	*	*	NS	*	*	**
SCE x LEV	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

For key to tests, see p 126

Table 58 The Significance of the Effect of the Source of Spring N on the Yield of Clover

	Cut	Source: Increasing Yield →		
1979	3	AN	LAS	LDS
		________	________	
			________	________
	5	AN	LAS	LDS
		________	________	
			________	________
Total		AN	LAS	LDS
		________	________	
			________	________
1980	1	AN	LAS	LDS
		________	________	
			________	________
	3	AN	LAS	LDS
		________	________	
			________	________
Total		AN	LAS	LDS
		________	________	
			________	________

Treatments not underlined by a common line are significantly different ($p < 0.05$) by Tukey's W procedure. Cuts in which differences between sources were not significant ($p > 0.05$) have been omitted.

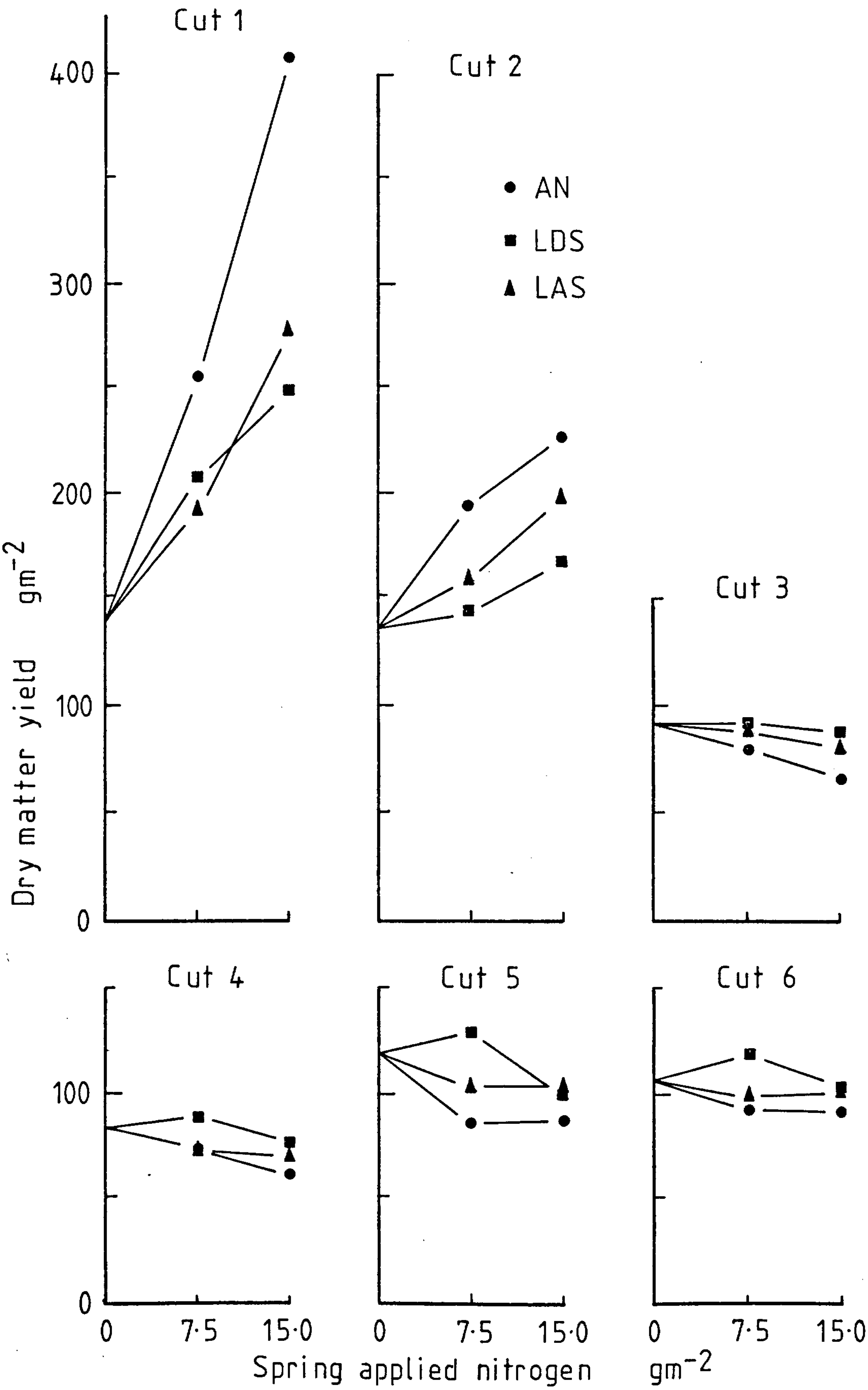


Fig 49 The relationship between spring applied nitrogen and the yield of the whole sward at each cut in 1979

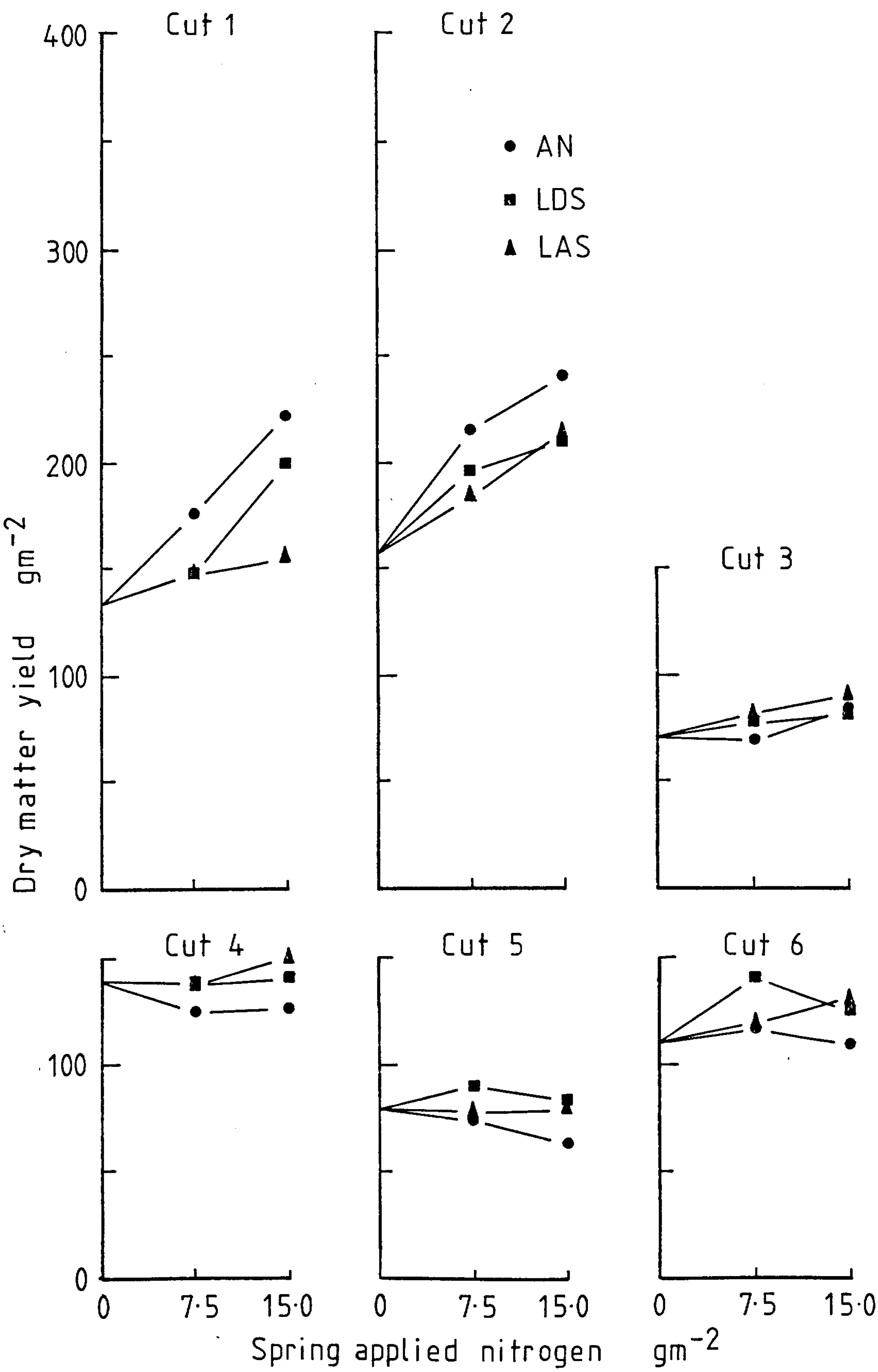


Fig 50 The relationship between spring applied nitrogen and the yield of the whole sward at each cut in 1980.

Table 59 Breakdown of AN, LDS and LAS Treatment Effects on the Yield of the Whole Sward

	Cut No													
	1979							1980						
	1	2	3	4	5	6	Tot.	1	2	3	4	5	6	Tot.
N RESP	***	***	NS	NS	*	NS	***	**	***	NS	NS	NS	NS	**
SCE	***	***	*	*	**	NS	**	*	**	NS	*	**	NS	NS
LEV	***	***	NS	*	NS	NS	***	**	**	*	NS	NS	NS	**
SCE x LEV	**	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS

For key to tests, see p 126

The marginal responses to the three sources of N (g DM g^{-1} N) in 1979 and 1980 are given in Table 60.

Table 60 The Significance and Effect of the Source of Spring N on the Yield of the Whole Sward

	Cut	Source: Increasing Yield →		
1979	1	LDS	LAS	AN
	2	LDS	LAS	AN
	3	AN	LAS	LDS
	4	AN	LAS	LDS
	5	AN	LAS	LDS
Total g DM g^{-1} N		LAS 6.9	LDS 8.4	AN 15.5
1980	1	LAS	LDS	AN
	2	LAS	LDS	AN
	4	AN	LDS	LAS
	5	AN	LAS	LDS
Total g DM g^{-1} N		LAS 7.3	AN 9.5	LDS 10.1

Treatments not underlined by a common line are significantly different ($p < 0.05$) by Tukey's W procedure. Cuts in which differences between sources were not significant ($p < 0.05$) have been omitted.

8.5.3 Total grass v total clover yield

The total clover yield (year 1 and 2) was plotted against the total grass yield for each treatment. The results from the two years were combined since treatment effects may have carried over from 1979 to 1980.

The relationship for inorganic fertilizer was estimated from the C, N1 and N2 treatment means. None of the sludge treatments deviated significantly ($p > 0.05$) from this relationship as determined by a t test so the relationship was recalculated to include a of the treatment means (Fig 51).

8.6 Discussion

The use of 30 cm diameter pots in this experiment invited the penalties of a high coefficient of variation of the results, edge effects and the possibility that the soil conditions and rooting depth would be unduly altered by the restriction of the pot wall and base. Despite relatively high coefficients of variation (particularly in the clover yield data) the experimental design and analytical techniques enabled the data to be adequately interpreted. The extent to which the pots interfered with the performance of the sward cannot be directly determined. In comparison with other studies (Armatage and Templeman, 1964, Brockman, 1974, Denehy and Morrison, 1979) the magnitude of the yields and the behaviour of the sward in response to the inorganic N were similar. The low clover yields at the beginning of the experiment (cut 1 and 2 in 1979) were probably due to the inhibition of leaf expansion by the cool spring weather (Haycock, 1981).

The response to spring N in the annual DM yield of the whole sward was low in comparison to that which can be obtained from a pure grass sward (Cooke, 1975, main field trial) due to the depression of the clover. The marginal responses (g DM g^{-1} N) were similar to those reported elsewhere (Armatage and Templeman, 1964, Denehy and Morrison, 1979).

The relationship between plots of total clover and total grass yield indicates that the effect of the sludge treatment on the sward can be adequately explained by a positive response of the grass to sludge N and a negative response of the clover to the increase in grass growth.

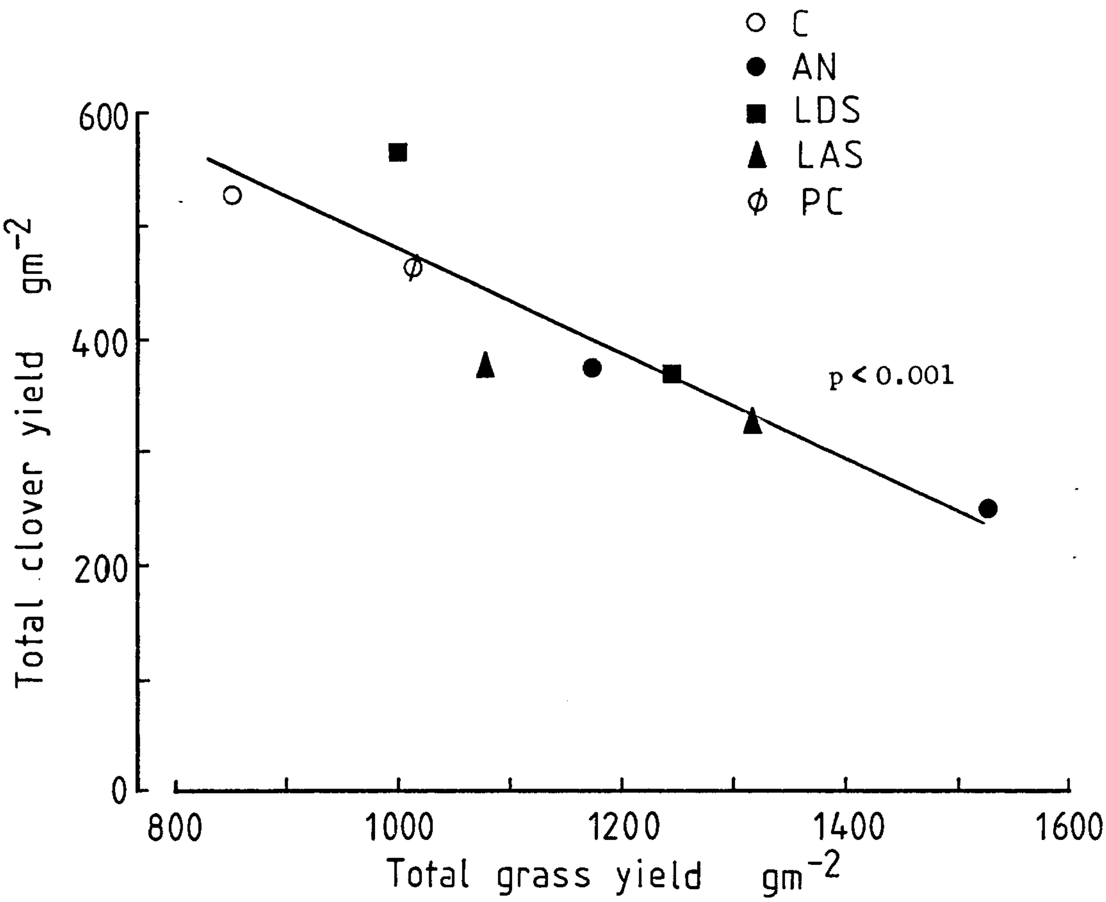


Fig 51 The relationship between the total grass yield and the total clover yield of the eight treatments.

However, the response of the grass to a source of N is determined by the availability of the N and the efficiency with which it is used to produce DM. The efficiency varies with changes in environmental conditions and the physiological status of the plant (Cooke, 1975). This means that the relationship between the sources of N in the response of the annual DM yield of grass depended not only on the total availability of N but also on the way it was released over the season.

In 1979 the response of the grass to each source in cut 1 and 2 reflected the difference in the availability of AN and sludge N. The response to the LAS compared to that of the AN and LDS was greater in cut 2 than in cut 1, suggesting the N was released more slowly from this source. Since the response to spring N was largely exhausted by cut 2, it was primarily the difference in the availability of N which determined the relative response to each source in the annual DM yield of the whole sward.

It is likely that the very dry weather in April and May 1980 was responsible for the poor response to N in cut 1, 1980 compared to 1979. The residual fertilizer effect of the spring N was greater in 1980 than in 1979, suggesting that in cut 1, 1980 much of the N was made unavailable by the low moisture content of the soil near the surface (Garwood and Williams, 1967a). Much of this N would have been remobilized when the rain returned. The drought may also have reduced the efficiency with which absorbed N was used to create DM.

The greater residual fertilizer effect of the sludges (particularly LAS) suggests that the dry weather had a greater effect on the sludge N than on the AN N. This is likely since from personal observations, most of the organic matter (and presumably the organic N) applied in the sludges was retained at the soil surface and was therefore susceptible to desiccation. This would have had a greater effect on the response to the LAS than on that to the LDS because more of the available

LAS N originated in the organic fraction (p 16). The effect of the drought on the sludge N in comparison with the AN N would have retained more of the potentially available N in the soil until more favourable growing conditions prevailed. Consequently, although the total availability of the sludge N was probably lower than that of the AN, this may have been partly offset by a greater efficiency of DM production from the sludge N. This may explain why the relationship between the response of the annual yield of the whole sward to the different sources of N in 1980 did not reflect differences in the N availability.

These results illustrate the error in assuming that the relationship between sources of N in the annual DM yield of a grass/clover sward reflects the availability of that N. This also offers an explanation for the wide difference in the DM response of grass/clover swards to sludge N to be found in the literature.

The poor response to the PC corresponds to that found by Geering and Kunzli (1967) and to the low N availability from this source determined in the main field trial (p 71).

8.7 Summary and conclusion

The DM yield responses obtained by applying the three types of sludge to a grass/clover sward were due solely to the positive response of the grass to sludge N and the negative response of the clover to the increased grass growth.

Due to the interaction of the source of N with environmental factors, the relationship between sources in the annual DM yield did not always reflect the differences in N availability.

The net DM yield advantage to be expected by applying sludges (or inorganic N fertilizers) to grass/clover swards is much smaller than that which can be expected from pure grass swards and is likely to be obtained at the expense of a reduction in the clover content of both sward and forage.

CHAPTER 9

FINAL DISCUSSION

9.1 The effectiveness of the sludges as N fertilizers

The current guidelines for the application of sludges to land (DOE/NWC, 1981) suggest that the mean availability of LDS N in the first growth period after application is about 85%. In the field trial reported earlier the availability of the N in a LDS was estimated to be about 46% on a sandy loam soil and about 35% on the clay soil (Table 15). These results together with those from other investigations (Edgar et al, 1981, Thomas, 1981) suggest that 85% is an overestimation of the mean availability of the N in LDS's. Furthermore, the use of a single, mean figure is likely to lead to gross under and over fertilization due to the wide range of LDS N availabilities which are likely to be encountered during disposal operations. As much of the variation in the availability of the LDS N between STW's is probably due to variations in the distribution of the N between the inorganic and organic forms, the availability of the N in LDS's from individual works should be estimated using a method which takes this distribution into account. The results of the field trial also suggest that the availability of LDS N may be influenced by soil type. However, this author suggests that methods of estimating the availability of LDS N should not take soil type into consideration until further investigations confirm this effect and determine the individual contributions of volatilization and denitrification.

The results of this and previous investigations suggest that the gaseous losses of N from LDS applied to grassland in the UK may be greater than has been recognised (p 13 and p 19). Further research is required to determine the magnitude and environmental factors affecting the gaseous losses of N from surface applied LDS.

Coker (1979) suggested that the availability of LDS N could be estimated as 100% x NH_4^+-N + 17% x organic N. Although this equation may require modification as a result of further research (see above), it is adequate as a temporary method of estimating the availability of the LDS N.

The current guidelines suggest that the availability of the N in undigested and dewatered sludges is 30% (DOE/NWC, 1981). In the field trial reported here the availability of LAS N was found to be about 50% on a sandy loam soil and about 47% on a clay soil (Table 15). A value of 50% can probably be adopted for operational purposes although this may lead to an underestimation of the availability of the N if primary sludge solids are not included in the aerobic treatment. The availability of the PC N was found to be about 16% on a sandy loam soil and about 20% on a clay soil (p 72). A value of 20% for the availability of the N in pressed co-settled sludges can probably be adopted for operational purposes although the availability may be lower if the sludge is dewatered on drying beds (p 16). The availability of dewatered LDS's is probably less than that of dewatered, co-settled sludges due to the loss of available N in the liquor (p 9).

The amount of available N which can be supplied to the farmer in sludge is limited by the restrictions on the application of PTE's laid down by the guidelines (DOE/NWC, 1981). The maximum permissible applications of the sludges used in the field trial are given in Appendix 8. If the recommendations in the guidelines had been followed, then the LDS, LAS and PC could have supplied a maximum of 120, 300 and 60 kg $ha^{-1}yr^{-1}$ available N. This indicates that the LDS and LAS could have supplied much or all of the fertilizer N requirement of most grassland farms whilst the contribution of the PC would have been rather small. The potential contribution of sludges from other STW's to the N requirement of grassland farms is difficult to assess due to the large variations in the availability of sludge N and concentration of PTE's in sludge and soil. Nevertheless, it is likely that the amount of available N which can be supplied by most LDS's and LAS's of primarily domestic origin is sufficient to be attractive to the grassland farmer whilst the potential of solid sludges as grassland fertilizers is limited.

9.2 The effect of sludge applications on the quantity and quality of grass

The results of the field trial suggest that when sludges are applied to grass for conservation, the available sludge N is used to create DM with an efficiency similar to that obtained when AN is used (p 79). However, when the sludges were applied to a more frequently cut sward in the grass/clover experiment, there was an interaction between the rate of release of the N from the different N sources (p 130). This interaction was not large and for practical purposes can probably be ignored.

The effect of the sludge applications on the concentration of CP, MADF, WSC, Ca, Mg and NO_3^--N in grass from the pure grass sward was similar to that of AN supplying the same amount of available N (p 105). The concentration of some PTE's in the grass receiving LDS was probably increased by the foliar retention of sludge solids (p 101). The practical importance of the foliar retention of sludge solids on the transfer of PTE's to livestock could not be assessed as the factors affecting foliar retention were not fully investigated. The results of a pot experiment suggest that the relationship between the foliar retention of sludge solids and the solids content of the sludge is non linear and differs between sludge types (Appendix 6). Further research is required to determine whether an alteration of the recommended minimum time between sludge application and grazing is necessary in some circumstances. The importance of the foliar retention of sludge solids as a pathway for the transmission of pathogenic organisms also deserves investigation.

9.3 The value of sludges as tools for the management of grass production.

The rapid release of N from the LDS and LAS found in the field trial (p 72) indicates that these sludges are potential tools for the management of grass production. The success of the sludges in this role depends upon the reliability of the sludges as N fertilizers in comparison with that of inorganic N fertilizers. The factors determining the reliability of both are:

1) supply

Most inorganic N fertilizers are easily stored so can be kept on the farm until needed. Sludges (exept solid sludges) cannot be conveniently stored without expensive lagoons so must be obtained from the STW when required. This may mean a delay in fertilization during periods of high demand if the farmer has to rely on the water authorities to transport and spread the sludge. The farmer may also be asked to accept sludge at times of the year when extra grass is not required or when fertilization is ineffective.

2) variation in composition

The variation in the composition of liquid sludges can be considerable (Table 7), even between batches taken from the same STW on the same day (Beckett and Johnston, 1980). In contrast, there is minimal variation in the composition of most inorganic N fertilizers.

3) accuracy of application rate

Modern farm machinery can apply solid inorganic N fertilizers with an accuracy of about ±5% whilst modern sludge spreading equipment can achieve an accuracy of about ±10% (Burrowes, pers. comm.). In practice, the accuracy of the application of both inorganic N fertilizer and sludge varies with the age and sophistication of the equipment and with the proficiency of the operator.

4) variations in the response of the grass

Considerable cut to cut variations in the response of the grass to both inorganic N fertilizer and the liquid sludges were found in the field trial. However, it was concluded that the variation in the response to the sludges was sufficiently greater than that of the inorganic N fertilizer that the value of the sludges as management tools would be reduced (p 68).

The combined effect of the variations associated with the sludges as described above makes it likely that they have considerably less value as management tools than inorganic N fertilizers. This lower reliability may be acceptable on extensively managed farms but is unlikely to be acceptable if the management is intensive. However, the use of sludge to fertilize spring silage may be acceptable where either system of management operates as there is often an opportunity to compensate for variations in the amount of grass produced by adjusting fertilizer applications later in the growing season.

There is probably some scope for improving the reliability of the sludges as N fertilizers. Much of the variation in the composition of sludges is probably introduced during the sewage treatment process and this may be reduced by a change in the management of existing STW's. Further improvement may be obtained by emphasizing the need for even and accurate applications of sludge when training the operators of sludge disposal equipment and through the routine replacement of old disposal machinery.

9.4 The residual effects of the sludge on the soil.

The effect of the sludge applications on the lime requirement of the soil was less deleterious than that of the applications of AN, even when the effects are adjusted to account for the differences in supply of available N (Table 15). On the sandy loam soil, applications of the PC and LAS may have increased the soil pH. A large rise in the soil pH above the recommended pH 6 is not desirable as the concentration of some trace elements in the grass may be reduced below the levels required for good animal nutrition. Routine monitoring of the soil from disposal sites is likely to detect such changes before problems arise.

In the trial reported here, the supply of available P in the sludges exceeded the loss of P in the grass harvested (p 110). The effect of the application of sludges from other STW's on the soil P reserve will probably depend on the balance between the depleting effect of the supply of available sludge N and the supplementing effect of the supply of available P. Basing sludge disposal policy on the assumption that sludge P is sufficient to replace P lost in grass harvested is unlikely to markedly affect the soil P reserve although the return of P in animal manure may lead to a substantial increase. The potential of the three sludges as P fertilizers can be calculated from the maximum permissible annual application rate (Appendix 8). The calculation, based on the total P in the sludge in the absence of estimates of the availability, suggests that the order of usefulness as P fertilizers decreases as LAS LDS PC. This is similar to the order of usefulness as N fertilizers (p 137).

The results of this investigation support the opinion expressed by Coker (1979) that the supply of durable organic matter in sludges used as N fertilizers is unlikely to produce substantial changes in soil physical properties (p 107). Agriculturally important changes in the earthworm population following such sludge applications are also unlikely (p 118).

Most of the PTE's added to the soil in the field trial remained in the soil (p 112). The increase in the soil PTE concentration would not have been expected to affect grass growth. In the absence of further sludge applications, the concentration of PTE's near the soil surface will probably decrease as earthworm activity redistributes sludge amended soil down the profile.

9.5 Future trends

In the near future, the application of sludges to grassland is likely to increase as alternative disposal methods become more expensive or are discontinued for environmental reasons. The implementation of stricter trade effluent control will probably reduce the concentration of PTE's in more sludges to levels which permit their use on grassland.

Following the recommendations of the 1977 guidelines (DOE/NWC, 1977) and the development of cheaper and smaller digesters, more sludge is likely to be digested prior to application to grassland. This would improve the value of the sludge as a N fertilizer as the reduced time required to be observed between application of the sludge and grazing would enable its use to be more easily integrated into the grassland farming system. Recent publications (eg Noone and Brade, 1981) have suggested that digester performance can be improved by the pre-digestion thickening of sludges and the use of high digester loading rates. The high loading rates lead to a more efficient mixing within the digester resulting in a sludge of consistent composition. The pre-digestion thickening reduces the need for post-digestion thickening, thereby retaining more of the NH_4^+-N in the sludge. The adoption of high rate digestion would therefore improve the value of the sludge to the grassland farmer.

For advisory purposes, ADAS assume that fertilizer applications are effectively mixed to a depth of 20cm in arable soils and 7.5cm in grassland soils. These mixing depths have been adopted by other EEC countries for the purposes of limiting the addition of PTE's in sludges. The current guidelines (DOE/NWC, 1981) do not contain formal recommendations for the application of PTE's to grassland so the sludges are applied in accordance with the restrictions placed on the addition of PTE's to arable soils. If future restrictions are based on the 7.5cm instead of 20cm effective mixing depth, the maximum permissible applications of sludge could fall by as much as two thirds. This would reduce the annual applications of many sludges to a level the farmers would probably not consider worth receiving.

Future investigations of the risks associated with sludge borne PTE's or pathogenic organisms may require an extension of the period after application before treated grass can be grazed. This would make the integration of sludge use into the grass farming system more difficult. The use of LDS on grass for grazing would be particularly affected as the current restrictions still permit the use of this sludge within a 21 day grazing cycle.

The ADAS assessment of the possible changes in UK agriculture in the period up to the year 2000 (MAFF, 1979) considered the current trend towards an increase in intensive grassland farming likely to continue. Whilst such a trend would increase demand for N fertilizer, it would also demand reliability of sludge supply and response. Increased production of animal slurry may compete with the sludges for suitable disposal opportunities.

This examination of future trends suggests that the use of the sludges on grassland will increase in the short term but may decrease in the long term. The factors leading to a decrease in sludge use are beyond the control of the water authorities but demand may be maintained if the effectiveness and reliability of the sludges as fertilizers and of the disposal operation are increased.

9.6 Conclusions

The results of this investigation suggest that LDS's and LAS's can be used effectively as N fertilizers for grassland but that the reliability of the sludges as tools for the management of grass production is lower than that of inorganic N fertilizers. The quality of the grass produced will be similar to that obtained through the use of an inorganic N fertilizer supplying the same amount of available N although the concentration of PTE's may occasionally be elevated by the foliar retention of LDS solids. The value of solid sludges as N or P fertilizers for grassland is small. The sludges have a less deleterious effect on the soil lime requirement than inorganic N fertilizers containing NH_4^+-N and supply sufficient P to replace losses in harvested grass. The effect of the application of sludges on the physical properties or earthworm population of grassland soils is unlikely to be of agricultural importance. Most of the PTE's applied in the sludges remained in the soil at the end of the field trial.

The true value of the sludges to the grassland farmer is determined by the balance between the costs and benefits of their application. The benefits include the value of the sludges as fertilizers whilst the costs include the time required to adjust the farm system to accommadate sludge usage, the risk of damage to accessways and to the soil structure through the passage of sludge disposal equipment and the risks associated with the sludge borne PTE's and pathogenic organisms.

Due to the trend towards increasing intensification of grassland farming, the use of sludge on grassland is likely to become less attractive unless the water authorities take measures to improve the effectiveness and reliability of both sludges and disposal operations.

CHAPTER 10

SUMMARY

The performance of liquid digested sludge (LDS), liquid activated (LAS) and pressed cake (PC) as nitrogen fertilizers for grassland was compared to that of ammonium nitrate (AN) in a field experiment on two contrasting soil types over two years. The trial had three components plus a control treatment. In component 1 the LDS and LAS were applied at rates of 100, 200 and 300 kg N ha^{-1} yr^{-1} in four equal applications. The AN was applied at rates of 100, 200, 300 and 400 kg N ha^{-1} yr^{-1} in four equal applications. In component 2, water and water plus AN at a rate of 200 kg N ha^{-1} yr^{-1} was applied to simulate the nitrogen x water interaction effect of the LDS. In component 3, LDS and LAS was applied in a single application of 150 kg N ha^{-1} yr^{-1} in the spring and PC was applied in a single application of 150 kg N ha^{-1} yr^{-1} (1978) or 400 kg N ha^{-1} yr^{-1} (1979) in the autumn. The treatments were applied to 1.5m x 10m plots and replicated four times at each site in a randomized block design. The grass was harvested four times per year.

The availability of the nitrogen in the LDS, LAS and PC as estimated from the nitrogen yield response was 46%, 50% and 16% respectively on the sandy soil and 35%, 48% and 20% respectively on the clay soil. Gaseous losses may have reduced the availability of the nitrogen in the liquid sludges on the clay soil. The water in the sludges had little effect on the availability of the sludge nitrogen.

The difference between the effect of the sludges and that of the AN on the dry matter yield and the concentration of crude protein, modified acid detergent fibre, water soluble carbohydrate, nitrate-nitrogen, calcium and magnesium in the grass was determined by the differences in the availability of the nitrogen. The LDS slightly raised the concentration of potentially toxic elements in the grass, probably due to the adherence of sludge solids to the leaves. In a laboratory experiment the amount of sludge solids retained on the leaves was found to vary with the sludge type and solids content.

The sludges increased the concentration of organic matter, potentially toxic elements and extractable phosphate in the soil and increased the density of the population of earthworms. The sludges did not acidify the soil as much as the AN.

The dry matter yield response in the field of a grass/clover sward in 30 cm diameter pots to the spring application of LDS, LAS and AN and an autumn application of PC was examined over two years. The LDS, LAS and AN was applied at the rate of 7.5 and 15.0 g N m^{-2} yr^{-1} and the PC at the rate of 36 g N m^{-2} yr^{-1}. The treatments were replicated five times and the pots harvested six times per year.

The response of the grass/clover sward to the nitrogen was lower than that of the pure grass sward and the response to the sludges depended on the rate of release of the sludge nitrogen.

It was concluded that the LDS and LAS could supply a substantial proportion of the annual nitrogen demand of the grassland farmer but that the variations in the availability of the sludge nitrogen might make it difficult to integrate its use into an intensive farming system.

REFERENCES

AGBIM, N.N., SABEY, B.R. and MARKSTROM, D.C. (1977) Land application of sewage sludge: V Carbon dioxide production as influenced by sewage sludge and wood waste mixtures. J. Environ. Qual. 6 (4) 446-451

ALLEN, S.E., GRIMSHAW, H.M., PARKINSON, J.A. and QUARMBY, C. (1974) Chemical analysis of ecological materials. Blackwell Sci.Pub., Oxford.

ALLISON, F.E. (1965) Evaluation of incoming and outgoing processes that affect soil nitrogen. In: Soil Nitrogen. Agronomy No 10. BARTHOLOMEW, W.V. and CLARK, F.E. (Eds), Madison, Wisconsin. Amer. Soc. Agron., 1965, 578-606.

ALLISON, F.E. (1973) Soil organic matter and its role in crop production. Elsevier Sci. Pub. Co., Amsterdam.

ANDERSEN, C. (1979) Cadmium, lead and calcium content, number and biomass, in earthworms (Lumbricidae) from sewage sludge treated soil. Pedobiologia 19, 309-319.

ANDERSEN, M.S. (1955) Sewage sludge for soil improvement. U.S.D.A. circular 972.

ANON. (1980) Copper deficiency in cattle. Vet. Rec. June 14, 1980 494-495.

ANSLOW, R.C. and GREEN, J.O. (1967) The seasonal growth of pasture grasses. J. agric. Sci., Camb. 68, 109-122.

ARMATAGE, E.R. and TEMPLEMAN, W.G. (1964) Response of grassland to nitrogenous fertilizer in the west of England. J. Brit. Grassld. Soc. 19, 291-297.

BARROW, V.L. (1955) Use of activated sludge as a fertilizer. World Crops Nov 1955, 435-437.

BEAUCHAMP, E.G., KIDD, G.E. and THURTELL, G. (1978) Ammonia volatilization from sewage sludge applied in the field. J. Environ. Qual. 7 (1), 141-146.

BEAUCHAMP, E.G., SOON, Y.K. and MOYER, J.R. (1979) Nitrate production from chemically treated sewage sludges in the soil. J. Environ. Qual. 8 (4), 557-560.

BECKETT, P.H.T. (1980) The statistical distribution of sewage and sludge analysis. Environmental Pollut. (Series B) 1, 27-35.

BECKETT, P.H.T. and JOHNSTON, N. (1980) Problems in field trials with sludge. In: Research seminar on crop trials. DOE/NWC, HMSO, Lond. 34-49.

BINNIE, R.C., HARRINGTON, F.J. and MURDOCH, J.C. (1974) The effect of cutting height and nitrogen level on the yield, in vitro digestibility and chemical composition of Italien ryegrass swards. J. Brit. Grassld. Soc. 29, 57-62.

BLACKMAN, G.E. (1936) The influence of temperature and available nitrogen supply on the growth of pasture in spring. J. agric. Sci., Camb. 36, 620-647.

den BOER, D.J. (1980) Effects of extreme rates of nitrogen applications on herbage nitrate content and health of grazing dairy cattle. In: The role of nitrogen in intensive grassland production. PRINS, W.H. and ARNOLD, G.H. (Eds), Centre for Agricultural Publishing and Documentation, Wageningen, 1980, 166.

BRADE, C.E. and NOONE, G.P. (1981) Anaerobic sludge digestion - need it be expensive? Making the most of existing resources. Water Pollut. Control 80 (1), 70-94.

BREMNER, J.M. (1965) Organic nitrogen in soils. In: Soil nitrogen Agronomy No 10, BARTHOLOMEW, W.V. and CLARK, F.E. (Eds), Madison, Wisconsin. Amer. Soc. Agron., 1965, 93-150.

BRENCHLEY, W.E. and RICHARDS, E.H. (1920) The fertilizing value of sewage sludges. J. Soc. Chem. Ind. 39 (13), 177-182.

BROADBENT, F.E. and CARLTON, A.B. (1980) Methodology for field trials with nitrogen-15 depleted nitrogen. J. Environ. Qual. 9 (2), 236-242.

BROCKMAN, J.S. (1974) Quantity and timing of fertilizer N for grass and grass/clover swards. In: Joint meeting of the Fertilizer Society and British Grassland Society, Fertilizer Soc. Proceedings No 142, 5-13.

BUNTING, A.H. (1963) Experiments on organic manures 1942-9. J. agric. Sci., Camb. 60, 121-140.

BURNS, R.E. and BOSWELL, F.C. (1976) Effect of municipal sewage sludge on rooting of grass cuttings. Agronomy Journal 68 (2), 382-384.

CHANEY, R.L., HORNICK, S.B. and SIMON, P.W. (1977) Heavy metal relationships during land utilization of sewage sludge in the northeast. In: Land as a waste management alternative. LOEHR, R.C. (Ed), Ann Arbor Sci. Pub. Inc., Ann Arbor, Mich. 1977, 283-314.

CHANEY, R.L. and LLOYD, C.A. (1979) Adherence of spray-irrigated liquid digested sludge to tall fescue. J. Environ. Qual. 8 (3), 407-411.

CHAUSSOD, R. (1979) Comment determiner l'azote ''mineralizable'' des boues residuaires? Paper given at a meeting of the Concerted Action Working Party 4, EEC, Dijon, 1979.

CHESTNUTT, D.M.B., MURDOCH, J.C., HARRINGTON, F.J. and BINNIE, R.C. (1977) The effect of cutting frequency and applied nitrogen on production and digestibility of perennial ryegrass. J. Brit. Grassld. Soc. 32,177-183.

COKER, E.G. (1966a) The value of liquid digested sewage sludge. I. The effect of liquid sewage sludge on growth and composition of grass/ clover swards in S.E. England. J. agric. Sci., Camb. 67, 91-97.

COKER, E.G. (1966b) The value of liquid digested sewage sludge. II. Experiments on ryegrass in S.E. England comparing sludge with fertilizers supplying equivalent nitrogen, phosphorus, potassium and water. J. agric. Sci., Camb. 67, 99-103.

COKER, E.G. (1966c) The value of liquid digested sewage sludge. III. The results of an experiment with barley. J. agric. Sci., Camb. 67, 105-107.

COKER, E.G. (1971) Utilization of sludge in agriculture. In: Sludge treatment and disposal. 4th Public Health Engineering Conf., University of Loughborough, 1971, 4.1-4.12.

COKER, E.G. (1979) The utilization of liquid digested sludge. In: Utilization of sewage sludge on land. BRUCE, A.M. (Ed), W.R.C. Stevenage. 110-129.

COKER, E.G. (1979) The design and establishment of field experiments on the agricultural use of sewage sludge. Tech. Rep. TR 123, W.R.C. Stevenage.

COOKE, G.W. (1975) Fertilizing for maximum yield. Crosby Lockwood Staples Lond.

CORNFIELD, A.H. (1959) Mineralization, during incubation, of the organic nitrogen compounds in soils as related to soil pH. J. Sci. Fd. Agric. 10, 27-28.

CORNFIELD, A.H., BECKETT, P.H.T. and DAVIS, R.D. (1976) Effect of sewage sludge on mineralization of organic carbon in soil. Nature 260, 518-520.

DAHLBERG, D. (1940) Statistical methods for medical and biological students. Bradford and Dickens, Lond.

DAMGAARD-LARSEN, S., LARSEN, K.E. and SØNDERGAARD KLAUSEN, P. (1979) Yearly application of sewage sludge on agricultural land. Tidsskrift for Planteavl 83, 349?386.

DAM KOFOED, A. (1981) Copper and its utilization in Danish agriculture. In: Copper in animal wastes and sewage sludge. L'HERMITE, P. and DEHANDTSCHUTTER, J. (Eds), D. Reidel Publ. Co., Dordrecht.

DAVIES, G.R. (1977) Pot experiments testing zinc, copper and nickel salts on the growth and composition of crops. In: Inorganic pollution and agriculture. ADAS open conf., Imperial Coll., 1977.

DEBRUCK, von J. (1972) Die verwertung der Nährstoffe in Abwasserschlamm. Landwirtschaftliche Forschung 25, 39-61.

DEINUM, B. and SIBMA, L. (1980) Nitrate content of herbage in relation to nitrogen fertilization and management. In: The role of nitrogen in intensive grassland production. PRINS, W.H. and ARNOLD, G.H. (Eds), Centre for Agricultural Publishing and Documentation, Wageningen, 1980, 95-102.

DENEHY, H.L. and MORRISON,J. (1979) The seasonal production of ryegrass-white clover swards given fertilizer in the spring. Grass and Forage Sci. 34 (1), 66.

DOE/NWC (1977) Report of the working party on the disposal of sewage sludge to land. H.M.S.O., Lond.

DOE/NWC (1978) Sewage sludge data and reviews of disposal to sea. H.M.S.O., Lond.

DOE/NWC (1981) Report of the sub-committee on the disposal of sewage sludge on land. H.M.S.O., Lond.

DOTY, W.T., BAKER, D.E. ans SHIPP, R.F. (1977) Chemical monitoring of sewage sludge in Pennsylvania. J. Environ. Qual. 6 (4), 421-426.

DOYLE, P.J., LESTER, J.N. and PERRY, R. (1978) Survey of literature on the disposal of sewage sludge on land. Final report to the DOE, Civil Engineering Dept., Imperial College, Lond.

EDGAR, K., HARKNESS, R.D. and FRAME, J. (1981) The manurial value of liquid anaerobically digested sludge on grassland in the west of Scotland. Paper presented at the XIV Int. Grassld. Congress, Lexington, Kentucky, June 15-24, 1981.

EDWARDS, C.A. and LOFTY, J.R. (1972) Biology of earthworms. Chapman and Hall, Lond.

EL-BASSAM, N. and TIETJEN, C. (1976) Municipal sludge as organic fertilizer with special reference to the heavy metal constituents. In: Soil organic matter studies, I.A.E.A., Vienna.

ELLIOTT, L.F., SCHUMAN, G.E. and VIETS, F.G. Jnr. (1971) Volatilization of nitrogen-containing compounds from beef cattle areas. Soil Sci. Soc. Amer. Proc. 35, 752-755.

ENGLISH, C.J. Jnr., MINER, J.R. and KOELLIKER, J.K. (1980) Volatile ammonia losses from surface-applied sludge. J. Water Pollut. Control Fed. 52 (9) 2340-2350.

ENNIK, G.K. (1970) White clover/grass relationships: A review. In: White clover research. LOWE, J. (Ed), Brit. Grassld. Soc., Hurley, Berks. 165-174.

ENNIK, G.K., GILLET, M. and SIBMA, L. (1980) Effect of high nitrogen supply on sward deterioration and root mass. In: The role of nitrogen in intensive grassland production. PRINS, W.H. and ARNOLD, G.H. (Eds), Centre for Agricultural Publishing and Documentation, Wageningen, 1980, 67-76.

EPSTEIN, E. (1975) Effects of sewage sludge on some soil physical properties. J. Environ. Qual. 4 (1), 139-142.

EPSTEIN, E., TAYLOR, J.M. and CHANEY, R.L. (1976) Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. J. Environ. Qual. 5 (4), 422-426.

EPSTEIN, E., KEANE, D.B., MEISINGER, J.J. and LEGG, J.O. (1978) Mineralization of nitrogen from sewage sludge and sludge compost. J. Environ. Qual. 7 (2), 217-221.

FURR, A.K., LAWRENCE, A.W., TONG, S.S.C., GRANDOLPHO, M.C., HOFSTADER, R.A., BOCHE, C.A., GUTTENHAM, W.H. and LISK, D.J. (1976) Multielement and chlorinated hydrocarbon analysis of municipal sewage sludge of American cities. Environ. Sci. and Tech. 10, 683-687.

FURRER, O.J. and BOLLIGER, R. (1978) Die wirtsomkeit des Stickstoff ins Klärschlamm. Schweizerische Landwirtschaftliche Forschung 17 (3/4), 137-147.

GALWARDI, E. (1974) Recovery of usable energy from treatment of municipal wastes. Thesis. University of Texas, Austin, Texas.

GARNER, H.V. (1966) Comparison of farmyard manure, sewage sludge and other organic manures. J. agric. Sci., Camb. 67, 267-280.

GARWOOD, E.A. and WILLIAMS, T.E. (1967a) Growth, water use and nutrient uptake from the subsoil by grass swards. J. agric. Sci., Camb. 69, 125-130.

GARWOOD, E.A. and WILLIAMS, T.E. (1967b) Soil water use and the growth of a grass sward. J. agric. Sci., Camb. 68, 281-292.

GARWOOD, E.A. and TYSON, K. (1973a) Losses of nitrogen and other plant nutrients to drainage from soil under grass. J. agric. Sci., Camb. 80, 303-312.

GARWOOD, E.A. and TYSON, K. (1973b) The response of S24 perennial ryegrass swards to irrigation. I. Effects of partial irrigation on DM yield and on the utilization of applied nitrogen. J. agric. Sci., Camb.

GARWOOD, E.A. and TYSON, K. (1977) High losses of nitrogen in drainage from soil under grass following a prolonged period of low rainfall. J. agric. Sci., Camb. 89, 767-768.

GARWOOD, E.A., SALETTE, J. and LEMAIRE, G. (1980) The influence of water supply to grass on the response to fertilizer nitrogen and nitrogen recovery. In: The role of nitrogen in intensive grassland production. PRINS, W.H. and ARNOLD, G.H. (Eds), Centre for Agricultural Publishing and Documentation, Wageningen, 1980, 59-66.

GEERING, von J. and KUNZLI, W. (1967) Gülle und Klärschlamm als Wiesendunger. Schweizerische Landwirtschaftliche Forschung 6 (1-4), 301-331.

GILMOUR, J.T. and GILMOUR, C.M. (1981) A simulation model for sludge decomposition in soil. J. Environ. Qual. 9 (2), 194-199.

GLATHE, H. and MAKAWI, A. (1963) Über die Wirkung von Klärschlamm auf Boden und Mikroorganismen. Zeitschrift für Pflanzernahrung Dungung 101, 109-121.

GRACEY, H.I., STEWART, T.A., WOODSIDE, J.D. and TOMPSON, R.H. (1976) The effect of disposing high rates of copper rich pig slurry on grassland on the health of grazing sheep. J. agric. Sci., Camb. 87, 617-623.

GREGORY, R and HARKNESS, N. (1979) Utilization of sewage sludge cake in agriculture. In: Utilization of sewage sludge on land. BRUCE, A.M. (Ed), W.R.C. Stevenage, 139-160.

GUCKERT, A., TOK, H.H. and JACQUIN, F. (1976) Biodegradation de polysaccharides bacteriens adsorbes sur une montmorillonite. In: Soil organic matter studies, I.A.E.A., Vienna.

GUPTA, S.C., DOWDY, R.H. and LARSEN, W.E. (1977) Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Sci. Soc. Amer. J. 41 (3), 601-605.

de HAAN, S. (1980) Sewage sludge as a phosphate fertilizer. Phosphorus in Agriculture 78, 33-41.

HALL, J.E. and COKER, E.G. (1981) Some effects of sewage sludge on soil physical conditions and plant growth. Paper presented at EEC Working Party 4 meeting in Vienna, 1981.

HARGROVE, W.L., KISSEL, D.E. and FENN, L.B. (1977) Field measurements of ammonia volatilization from surface applications of ammonium salts to a calcareous soil. Agronomy Journal 69 (3), 473-476.

HARTENSTEIN, R., NEUHAUSER, E.F. and COLLIER, J. (1980) Accumulations of heavy metals in the earthworm Eisenia foetida . J. Environ. Qual. 9 (1), 23-26.

HAUK, R.D. (1981) Nitrogen fertilizer effects on the nitrogen recycling processes. In: Terrestrial nitrogen cycles. CLARK, F.E. and ROSSWALL, T. (Eds), Ecol. Bull. (Stockholm) 33, 551-562.

HAYCOCK, R. (1981) Environmental limitations to spring production in white clover. Paper given at British Grassland Society conf., Plant physiology and herbage production, Nottingham University, 7-9 April, 1981.

HECK, J.P., BARTHELEMY, J.P. and ROCHE, M. (1978) Characterisation de certains elements biogenes majeurs et metaux lourds. Annales de Gembloux 84, 77-92.

HINESLEY, T.D. and SOSEWITZ, B. (1969) Digested sludge disposal on crop land. J. Water Pollut. Control Fed. 41 (1),822-830.

HINESLEY, T.D., BRAIDS, O.C. and MOLINA, J.E. (1971) Agricultural benefits and environmental changes resulting from the use of digested sewage sludges on field crops. U.S.E.P.A Rep. No. SW 30D

HODGSON, J., BAKER, R.D., DAVIES, ALISON, LAIDLAW, A.S. and LEAVER, J.D. (1981) Sward measurement handbook. British Grassland Society, Hurley, Berks.

HOLMES, W. (1980) Introduction to Grass, its production and utilization, HOLMES, W. (Ed), Blackwell Scientific Publ., Oxford.

HSIEH, Y.P., DOUGLAS, LOWELL A. and MOTTO, HARRY L. (1981a) Modeling sewage sludge decomposition in soil I. Carbon transformations. J. Environ. Qual. 10 (1), 59-64.

HSIEH, Y.P., DOUGLAS, LOWELL,A. and MOTTO, HARRY L. (1981b) Modeling sewage sludge decomposition in soil II. Nitrogen transformations.

HUCKER, T.W.G. and CATROUX, G. (1981) Phosphorus in sewage sludge and animal waste slurries. Reidel Publ. Co., Dordrecht.

HUNTER, J.W. and HEUKELEKIAN, H. (1965) The composition of domestic sewage fractions. J. Water Pollut. Control Fed. 37, 1142-1163.

JONES, S.G., BROWN, K.W., DEVEL, L.E. and DONNELLY, K.C. (1979) Influence of simulated rainfall on the retention of sludge heavy metals by leaves of forage crops. J. Environ. Qual. 8 (1), 69-72.

KELLER, P. (1979) Le controle des boues d'epuration: Experiences faites au cours d'une annee. Paper given at meeting of the Concerted Action Working Party 4, EEC, Dijon, 1979.

KELLING, K.A., PETERSON, A.E., WALSH, L.M., RYAN, J.A. and KEENEY, D.R. (1977) A field study of the agricultural use of sewage sludge: I. Effects on crop yield and uptake of N and P. J. Environ. Qual. 6 (4), 339-345.

KEMP, A., GEWINK, J.H., MALESTEIN, A. and van 't KLOOSTER, A.Th. (1978) Grassland production and nitrate poisoning in cattle. Proc. 7th Gen. Meeting, Europ. Grassld. Fed., Ghent 9, 1-9.15.

KING, L.D. and MORRIS, H.D. (1972) Land disposal of liquid sewage sludge I. The effect on yield, <u>in vivo</u> digestibility and chemical composition of Coastal Burmudagrass (<u>Cynodon dactylon</u> L. Pers.).

KING, L.D. (1973) Mineralization and gaseous losses of nitrogen in soil applied liquid sewage sludge. J. Environ. Qual. 2 (3) 356-358.

KING, L.D., RUDGERS, L.A. and WEBBER, L.R. (1974) Applications of municipal refuse and liquid sewage sludge to agricultural land. I. Field study. J. Environ. Qual. 3 (4), 361-366.

KLADIVKO, E.J. and NELSON, D.W. (1979) Changes in soil properties from applications of anaerobic sludge. J. Water Pollut. Control Fed. 51 (2), 325-332.

LARSEN, K.E. (1979) Nitrogen value of sewage sludges: Danish experiments on sludge valorization. Paper given at a meeting of Concerted Action Working Group 4, EEC, Dijon, 1979.

LARSEN, K.E. (1981) Phosphorus effect of animal manures and sewage sludge. In: Phosphorus effect of animal manure and sewage sludge. HUCKER, T.W.G. and CATROUX, G. (Eds), Reidel Publ. Co., Dordrecht.

LAUER, D.A., BOULDIN, D.R. and KLAUSNER, S.D. (1976) Ammonia volatilization from dairy manure spread on the soil surface. J. Environ. Qual. 5 (2), 134-141.

LUEBS, R.E., DAVIS, K.R. and LAAG, A.E. (1973) Enrichment of atmosphere with nitrogen compounds volatilized from a large dairy area. J. Environ. Qual. 2 (1), 137-141.

LUNT, H.A. (1959) Digested sewage sludge for soil improvement. Conn. Agric. Expt. Sta. Bull. No. 622.

LYNCH, D.L. and COTNOIR, L.T. (1956) The influence of clay minerals on the breakdown of certain organic substrates. Soil Sci. Soc. Amer. Proc. 20, 367-376.

MAFF (1973) The analysis of agricultural materials. Tech. Bull. 27, H.M.S.O., Lond.

MAFF (1975) Lime and fertilizer recommendations for arable crops and grassland based on soil analysis. General Laboratory Services, Booklet No. 1, H.M.S.O., Lond.

MAFF (1975) Grass as a feed. Grassland practice No. 7, H.M.S.O., Lond.

MAFF (1978) The use of sewage sludges as a fertilizer. AF51, H.M.S.O., Lond.

MAFF (1979) Agriculture in 2000 AD (paper 1). In: Royal Commision on Environmental Pollution 7th Report. 242-257

MAGDOFF, F.R. and CHROMEC, F.W. (1977) Nitrogen mineralization from sewage sludge. J. Environ. Sci. Health A12 (4/5), 191-201.

MAGDOFF, F.R. and AMADON, J.F. (1980) Nitrogen availability from sewage sludge. J. Environ. Qual. 9 (3), 451-454.

MARKS, M.J. (1978) Evaluation of the nitrogen and phosphorus content of dried, pelleted sewage sludge. Soil Science Ann. Rep., Wye Sub-centre, MAFF.

MILLER, R.H. (1974) Factors affecting the decomposition of an anaerobically digested sewage sludge in soil. J. Environ. Qual. 3 (4), 376-380.

MITCHELL, M.J., HARTENSTEIN, R., SWIFT, B.L., NEUHAUSER, E.F., ABRAMS, B.I., MULLIGAN, R.M., BROWN, B.A., CRAIG, D. and KAPLAN, D. (1978) Effects of different sewage sludges on some chemical and biological characteristics of soil. J. Environ. Qual. 7 (4), 551-559.

MITCHELL, M.J., HORNOR, S.G. and ABRAMS, B.I. (1980) Decomposition of sewage sludge in drying beds and the potential role of the earthworm, Eisenia foetida. J. Environ. Qual. 9 (3), 373-378.

MONTIETH, H.D. and STEVENSON, J.P. (1980) Mixing efficiency in full-scale anaerobic digesters by tracer methods. J. Water Pollut. Control Fed. 53 (1), 78-84.

MOREL, J.L. and JACQUIN, F. (1976) Etude de la mineralisation dans un sol agricole de boues residuaires d'origines diverses. Bull. de l'E.N.S.A.I.A. de Nancy 18 (1/2), 83.

MOREL, J.L., GUCKERT, A. and SEDOGO, M. (1978) Effects de l'epandage de boues residuaires urbaines sur l'etat physique du sol. Bull. de l'E.N.S.A.I.A. de Nancy 20 (1/2), 13-19.

MOREL, J.L., GUCKERT, A., SIBOUT, V. and JACQUIN, F. (1978) Possibilites de valorisation agricole de boues residuaires urbaines. I. Etude des variations de la composition des boues. Bull. de l'E.N.S.A.I.A. de Nancy 20 (1/2), 21-29.

MORRISON, J., JACKSON, M.V. and SPARROW, P.E. (1980) The response of perennial ryegrass to fertilizer nitrogen in relation to climate and soil. Report of the joint ADAS/GRI grassland manuring trial GM 20, G.R.I. Technical Rep. No. 27, Hurley.

NELMES, A.J., BUXTON, R. St. J., FAIRWEATHER, F.A. and MARTIN, A.E. (1974) The implications of the transfer of trace metals from sewage sludge to man. Trace Subs. Environ. Health 8, 145-153.

NIAB (1978) Grasses and legumes for conservation 1978/9. N.I.A.B., Cambridge.

OSBOURNE, D.F. (1980) The feeding value of grass and grass products. In: Grass, its production and utilization. HOLMES, W. (Ed), Blackwell Scientific Publ., Oxford.

PAIN, B.F. (1974) Effects of cow slurry on earthworms (Lumbricidae) in grassland. J. Sci. Fd. Agr. 25, 1193.

POMMEL, B. (1981) The phosphorus value of sludges in relation to their metal contents. In: Phosphorus in sewage sludge and animal wastes. HUCKER, T.W.G. and CATROUX, G. (Eds), Reidel Publ. Co., Dordrecht.

PREMI, P.R. and CORNFIELD, A.H. (1969) Incubation study of nitrification of digested sewage sludge added to soil. Soil Biol. Biochem. 1, 1-4.

PREMI, P.R. and CORNFIELD, A.H. (1972) Incubation study of nitrogen mineralization in soil treated with dried sewage sludge. J. Environ. Pollut. 2 (1), 1-5.

RAW, F. (1959) Estimating earthworm populations by using formalin. Nature, Lond. 184, 1661.

REDDY, K.R., KHALED, R. and OVERCASH, M.R. (1980) Carbon transformations in the land areas receiving organic wastes in relation to nonpoint source pollution: A conceptual model. J. Environ. Qual. 9 (3), 434-442.

REID, D. (1966) The response of herbage yield and quality to a wide range of nitrogen application rates. In: Proc. 10th Int. Grassld Congr., Helsinki, 1966, 209-213.

RICHARDSON, S.J. (1980) Composition of soils and crops following treatment with sewage sludge. In: Inorganic pollution and agriculture. ADAS open conf., Imperial Coll., 1977.

ROYAL COMMISION ON SEWAGE DISPOSAL (1908) 4th Report. H.M.S.O., Lond.

RUDOLFS, W. and GEHM, H.W. (1942) The chemical composition of sewage sludges with special reference to their phosphoric acid content. New Jersey Agric. Exp. Sta. Bull. No. 699.

RUNDLE, H., CALCROFT, M. and HOLT, C. (1981) Agricultural disposal of sludges on a historic sewage farm. Paper given to I.W.P.C. East Midlands Branch, 28th April, 1981.

RYAN, J.A., KEENEY, D.R. and WALSH, L.M. (1973) Nitrogen transformations and availability of an anaerobically digested sludge in soil. J. Environ. Qual. 2 (4), 489-492.

RYAN, J.A. and KEENEY, D.R. (1975) Ammonia volatilization from surface applied wastewater sludge. J. Water Pollut. Control Fed. 47 (2), 386-393.

SCHAUMBERG, GENE E., LE VESQUE-MADOVE, C.S., SPOSITO, GARRISON and LUNT, L.J. (1980) Infrared spectroscopic study of the water-soluble fraction of sludge-soil mixtures during incubation. J. Environ. Qual. 9 (2), 297-303.

SLUIJSMAN, C.M.J. (1981) Introduction to Phosphorus in sewage sludge and animal wastes. HUCKER, T.W.G. and CATROUX, G. (Eds), Reidel Publ. Co., Dordrecht.

SOMMERS, L.E., NELSON, D.W. and YOST, K.J. (1976) Variable nature of chemical composition of sewage sludges. J. Environ. Qual. 5 (2), 303-306.

SOMMERS, L.E. (1977) Chemical composition of sewage sludges and analysis of their potential use as fertilizers. J. Environ. Qual. 6 (2), 225-231.

SOMMERS, L.E., NELSON, D.W. and SILVIERA, D.J. (1979) Transformations of carbon, nitrogen and metals in soils treated with waste materiels. J. Environ. Qual. 8 (3), 287-294.

SOON, Y.K., BATES, T.E. and MOYER, J.R. (1978) Land application of chemically treated sewage sludge. II. Effects on plant and soil phosphorus, potassium, calcium, magnesium and soil pH. J. Environ. Qual. 7 (2), 269-273.

SPEDDING, C.R.W. and DIEKMAHNS, E.C. (Eds) (1972) Grasses and legumes in British agriculture. Bull 49, Commonw. Bur. Past. Fld. Crops, Farnham Royal.

STEWART, N.E., BEAUCHAMP, E.G., CORKE, C.T. and WEBBER, L.R. (1975a) Nitrate nitrogen distribution in corn land following applications of digested sewage sludge. Can. J. Soil Sci. 55, 287-294.

STEWART, N.E., CORKE, C.T., BEAUCHAMP, E.G. and WEBBER, L.R. (1975b) Nitrification of sewage sludge using miscible displacement and perfusion techniques. Can. J. Soil Sci. 55 (4), 467-472.

SUESS, A. (1979) The nitrogen value of sludges. Paper given at the Concerted Action Working Party 4 meeting, EEC, Dijon, 1979.

SWANWICK, J.D., SHURBEN, D.G. and JACKSON, S. (1969) A survey of the performance of sewage sludge digestion in Great Britian. Water Pollut. Control 68 (6), 639.

TERMAN, G.L. (1979) Volatilization losses of nitrogen as ammonia from surface applied fertilizers, organic amendments and crop residues. Adv. in Agron. 31, 189-223.

TERRY, R.E., NELSON, D.W., SOMMERS, L.E. and MOYER, G.J. (1978) Ammonia volatilization from wastewater sludge applied to soils. J. Water Pollut. Control Fed. 50 (12), 2657-2665.

TERRY, R.E., NELSON, D.W. and SOMMERS, L.E. (1979) Decomposition of anaerobically digested sewage sludge as affected by soil environmental conditions. J. Environ. Qual. 8 (3), 342-347.

TERRY, R.E., NELSON, D.W. and SOMMERS, L.E. (1981) Nitrogen transformations in sewage sludge-amended soils as affected by soil environmental factors. Soil Sci. Soc. Amer. J. 45, 506-513.

THOMAS, W.M., (1981) The biological and chemical effects of digested sludge as a nitrogenous fertilizer on grass crops using in situ lysimeters. Ph.D. Thesis, Luton Coll., 1981.

TUKEY, J.W. (1949) Comparing individual means in analysis of variance. Biometrics 5, 99-114.

TUNNEY, H. (1976) Fertilizer value of animal manures. Proc. EEC seminar on landspreading of manures, Italy, Sept. 1976. 175-178.

UNWIN, R.J. (1977) Copper in pig slurry: Some effects and consequences of spreading on grassland. In: Inorganic pollution and agriculture. ADAS open conf., Imperial Coll., 1977.

VIETS, F.G. (1965) The plants need for and use of nitrogen. In: Soil nitrogen. BARTHOLOMEW, W.V. and CLARK, F.E. (Eds), Madison, Wisconsin. Amer. Soc. Agron., 1965, 508-546.

WALKER, T.W., ADAMS, A.F.R. and ORCHISTON, H.D. (1956) Fate of labelled nitrate and ammonium nitrogen when applied to grass and clover grown seperately and together. Soil Sci. 81, 339-351.

WEBBER, J. (1977) Metals in sewage sludge applied to the land and their effects on crops. In: Inorganic pollution and agriculture. ADAS open conf., Imperial Coll., 1977.

WHITEHEAD, D.C. (1970) The role of nitrogen in grassland productivity. Bull. 48, Commonwealth Bur. Past. Fld. Crops, Farnham Royal.

WILLIAMS, J.H. and COKER, E.G. (1981) Phosphorus in sewage sludge and its behaviour in soils. In: Phosphorus in sewage sludge and animal wastes. HUCKER, T.W.G. and CATROUX, G. (Eds), Reidel Publ. Co., Dordrecht.

WILSON, D.O. (1977) Nitrification in soil treated with domestic and industrial sewage sludge. Environmental Pollut. 12, 73-82.

WONG, M.H. and YIP, S.W. (1980) Seasonal fluctuations of the properties of sewage sludge. Resource Recovery and Conservation 5, 279-284.

WRIGHT, M.J. and DAVISON, K.L. (1964) Nitrate accumulation in crops and nitrate poisoning in animals. Adv. in Agron. 16, 197-247.

GLOSSARY

Anaerobic digestion The decomposition of sludge organic matter by mesophilic micro-organisms under anaerobic conditions.

Availability The amount of an element or compound which can be absorbed by plants or micro-organisms.

Bulked sample The result of the combination and mixing of several smaller samples.

Bulk density The weight of soil per unit volume.

Cation exchange capacity The capacity of the soil to hold and exchange positively charged ions.

Coefficient of variation The standard error divided by the mean.

Conditioning The addition of a substance to a sludge to facilitate its dewatering.

Conservation The treatment of fodder to enable its storage as a winter feed.

Copperas $FeSO_4.7H_2O$

Denitrification The conversion of NO_3^--N (plant available) to N_2 and N_2O (gases) by micro-organisms.

Digestibility The amount of the fodder which can be digested in the cow.

Ensiling The making of silage.

E_N The efficiency with which N absorbed by the grass is used to create dry matter.

Floc Clumps of aerobic micro-organisms within an activated treatment tank.

Immobilization The conversion of mineral (plant available) N to organic (unavailable to plant) N.

Maintenance fertilizer The amount of fertilizer required to replace nutrients lost in grazed or cut grass.

Marginal response   The increase in DM yield per weight of fertilizer N applied.

Mineral N NH_4^+- or NO_3^--N

Nitrification   The formation of NO_3^--N by micro-organisms.

N source   Material supplying N.

Pathogens   Organisms capable of causing desease.

Phytotoxic   Toxic to plants.

Site/cut   The results from one cut at one site.

Skewed   A larger number of either high or low values than would be expected by chance.

Tiller   Vegatative growth of grasses.

Winterkill   The death of grass by whatever cause during winter.

APPENDIX 1

Recommended maximum permissible additions of elements in sludge to uncontaminated non - calcareous soils over a period of 30 years or more.

Element	Uncontaminated soil background concentration	Maximum permissible addition of element
	$mg\ l^{-1}$	$kg\ ha^{-1}$
	Extractable	Total
Zn	2.5	560*
Cu	5	280*
Ni	1	70*
Zn equivilent	20.5	560
B	1	4.5 (1st yr)
		3.5 (2nd yr)
	Total	
Cr	100	1000
Cd	1	5
Pb	50	1000
Hg	0.1	2
Mo	2	4
As	5	10
F	200	600
Se	0.5	5

* Twice this limit permitted on permenant grassland

Extractable - amount extracted by EDTA, B extracted by hot water

Total - amount extracted by strong acid, F by fusion and selective ion electrode, B by hot water

Reproduced from DOE/NWC (1981)

APPENDIX 2

Calibration of the Saturometer

A sample of air dried soil (about 200g dry weight) from each site, ground to pass a 2mm sieve was mixed to a thick slurry with distilled H_2O. The slurry of each soil type was packed into a piece of PVC tubing (15cm by 4cm dia.) and three readings of the Saturometer were obtained by inserting the probe into the packed soil. A sample of the slurry (about 10g wet weight) was removed for a gravimetric determination of the soil moisture content. The slurries were then removed from the tubes and dried for a short time in an oven at 90^oC. They were then repacked in the tubes and further readings obtained as before. This procedure was repeated to obtain the calibration curves shown in Fig 52.

The soil moisture contents determined by the Saturometer (Fig 6) were always lower than the soil moisture at field capacity determined on intact soil cores on a sand bath (Table 8) although the soils were probably at or near field capacity at the beginning of the 1979 growing season. The Saturometer readings may therefore not have accurately recorded the soil moisture content although changes in the soil moisture were detected. This author has therefore accepted the Saturometer readings as a rough guide to the changes in soil moisture content.

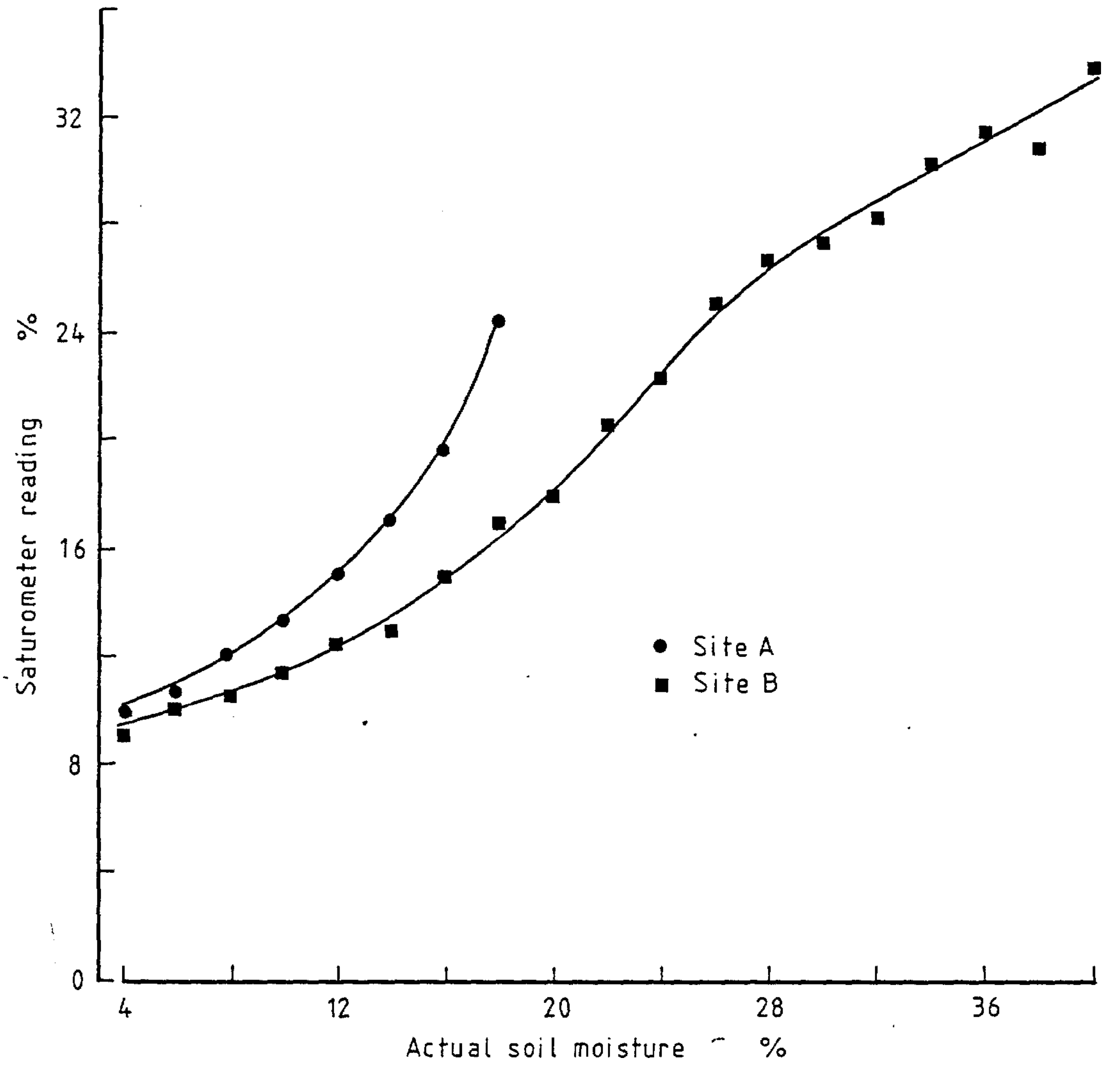


Fig 52 Saturometer calibration lines

APPENDIX 3

The physical breakdown of PC solids

A sample of PC (about 2kg dry weight) was taken from the load obtained for the autumn 1979 application (p 49) and was chopped to pass a 2.54cm sieve. Lumps passing a 0.7cm sieve were discarded. The chopped sludge was dried overnight at about 80°C in a forced draught oven. Forty samples of the sludge (about 30g dry weight each) were weighed accurately and the sealed in polythene bags for transportation to the sites.

At both sites, 20 squares of plastic mesh (15cm x 15cm, 0.7cm mesh) were pinned down in a four by five pattern. In early January 1980 one sample of dried, weighed sludge was spread on each square. In late March, early June, mid July, late August and early October the PC solids remaining on four randomly selected squares were collected, dried at 100°C and weighed.

The loss of PC solids from the mesh squares over time is shown in Fig 24 . A two - way analysis of variance (site x sampling date) on the arcsin transformed results found there to be significant ($p < 0.001$) differences between the sampling dates but no significant ($p < 0.05$) difference between the sites and no significant ($p < 0.05$) site x sampling date interaction.

These results are discussed on p 71.

APPENDIX 4

The determination of the amount of exchangeable NH_4^+-N held on the LDS solids.

Method

Eight samples of LDS (about 1l each) representing a range of solids contents were obtained from the settling tanks at the Monkmoor STW (p 39). The solids content of each sample was determined by the method given on p 51).

A sub-sample of sludge (100 cm^3) was diluted to 200 cm^3 with 20% $^w/v$ KCl and shaken for 30 mins. A further sub-sample of sludge was diluted to 200 cm^3 with distilled H_2O and also shaken for 30 mins. Samples of these KCl and H_2O extracts were spun at 3000 rpm for 5 mins. to send down the solid fraction of the sludge. The liquid fraction was analysed for NH_4^+-N on the auto-analyser at the Severn Trent Water Authority Strongford Laboratory.

The difference between the amount of NH_4^+-N in the KCL and H_2O extracts was taken as a measure of the exchangeable NH_4^+-N.

Results

The relationship between the exchangeable NH_4^+-N and the solids content of the LDS is shown in Fig 53. This relationship was used to correct the 1979 sludge analyses to account for the exchangeably held NH_4^+-N.

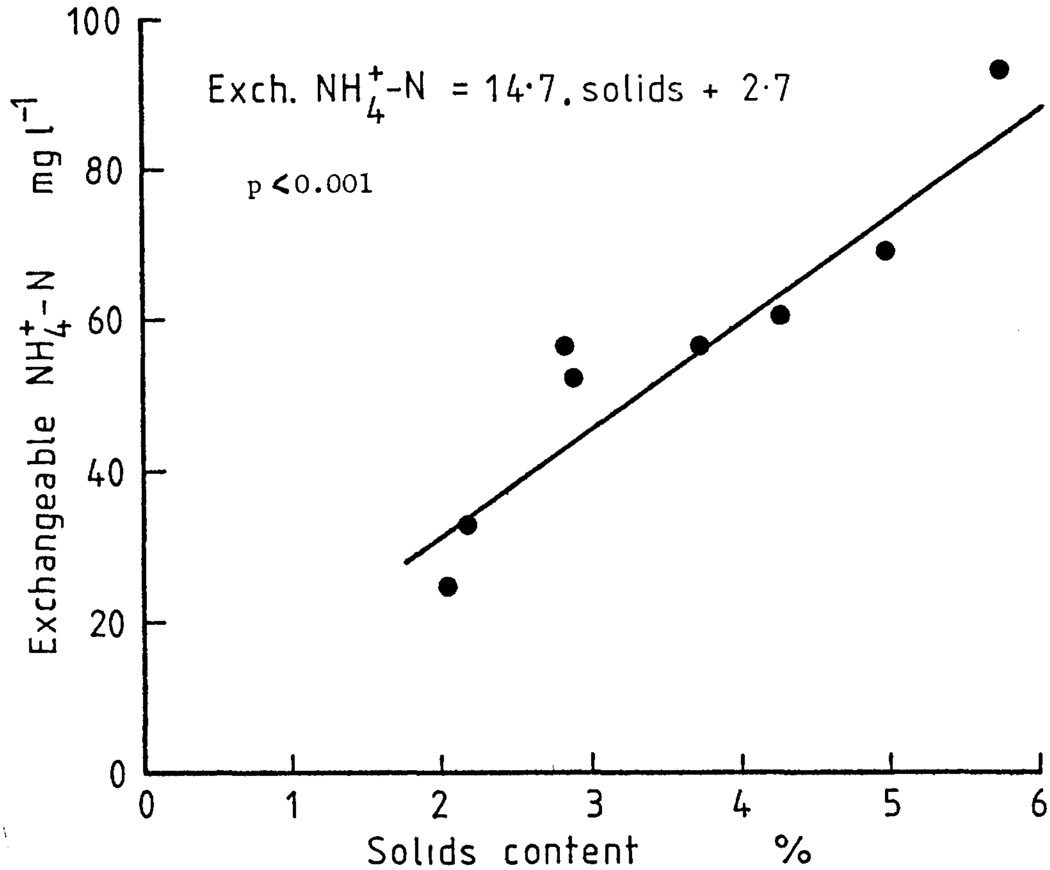


Fig 53 The relationship between the exchangeably held NH_4^+-N and the solids content of the LDS.

APPENDIX 5

Foliar retention of sludge solids

Introduction

The purpose of this experiment was to examine the effect of sludge type and solids content on the amount of sludge solids retained on the grass leaves. To avoid possible interactions between the foliar retention and the efficiency of sludge spreading, sufficient sludge was applied to ensure that all leaves were covered. The test grass was grown from seed in pots in the glasshouse to obtain as uniform a canopy as possible.

Method

Grass seed (Lolium perenne cv S23) was sown into a circle of about 1.5cm dia in the centre of a 10.5cm dia pot filled with John Innes No 2 compost. After germination the number of plants was reduced to seven per pot. The grass was grown in the glasshouse (16hr daylength, about 18^{o}C) for eight weeks and was cut to a height of 3cm every week from the fourth to eighth week. The final cut was made immediately before the treatments were applied.

Samples of LDS and LAS (about 10l) were obtained from the Monkmoor and Market Drayton STW's (see p 39) and were allowed to stand for 12 hours. The top water was then removed and a subsample (about 1l) taken, avoiding the heterogenous material at the bottom of the container. A range of ten LDS's and seven LAS's of different solids contents were prepared. To obtain the highest solids contents it was necessary to amend the samples with sludge solids spun out at 3000rpm for 3 min. The remainder of the range was prepared by diluting the settled sludge with top water. Distilled water was used for a control treatment. A sample of each of the range of sludges (about 5cm^3) was removed for a gravimetric determination of the solids content.

Each of the range of sludges was applied to two pots by immersing the grass leaves in the sludge sample. The leaves were immersed in the sludges of high solids content with the aid of a smooth ended glass rod. Treated pots were drained upended for 5 mins then placed in a controlled environment cabinet overnight to dry. The replicates were blocked between two cabinets. The following day the grass was cut to a height of 0.5cm above the soil surface. The harvested grass was soaked in 2% Decon solution ($10cm^3$) for 30 mins then each leaf was gently brushed clean with a soft haired brush. The washed grass and the washings were dried overnight at 100^oC and the dry weights determined.

Results and discussion

The relationships between the amount of foliar retention of sludge solids (expressed as the weight of sludge per unit weight of grass) and the type and solids content of the sludge are shown in Fig 44. There was a significant ($p < 0.001$) regression between the natural logarithm of the foliar retention of sludge solids and the solids content of both sludges.

The management of the test plants encouraged the leaves to adopt an erect posture and wet sludge, even at the higher solids contents, did not readily adhere to the smooth, steep surface presented. Sludge did readily collect at the bases of the leaves and this progressively increased as the solids content of the sludge increased. The dramatic rise in the foliar retention at the higher solids contents of both sludges was associated with the binding together of adjacent leaves by a layer of sludge.

Given the strength with which LDS solids have been found to be held on grass leaves if allowed to dry (Chaney and Lloyd, 1979), it was considered necessary to examine the success of the washing procedure in recovering the adhering solids. Fig 44 also shows the results of an earlier experiment conducted under similar conditions but in which the LDS was allowed to drain but not dry prior to washing. The similarity in the results from the two experiments suggests that the washing method adopted recovered most or all of the adhering sludge solids.

The relevance of the results of this experiment is discussed on p 101.

APPENDIX 6

Potentially toxic elements added to the soil in the LDS3, LAS3 and PC treatments.

	PTE added* g		
Element	Sludge		
	LDS3	LAS3	PC
Zn	24228	7286	11624
Cu	7851	5998	6045
Ni	983	299	323
B	1614	1437	530
Cr	3533	567	665
Cd	171	31	49
Pb	9206	3440	4795

* Mean of Site A and B

APPENDIX 7

Permissible additions of sludge to the experimental sites

Element	Maximum addition t dry solids $ha^{-1}y^{-1}$					
	Site					
	A			B		
	Sludge					
	LDS	LAS	PC	LDS	LAS	PC
Zn*	16.2	33.0	29.1	16.0	32.6	28.8
Cu*	26.7	20.8	28.6	26.3	20.4	26.3
Ni*	51.4	103.7	141.4	51.4	103.7	141.4
Zn eq.	8.3	11.1	12.9	8.1	10.8	12.5
B 1st yr	60.4	41.7	166.1	60.4	41.7	166.1
2nd yr	47.0	32.4	129.0	47.0	32.4	129.0
Cr	242.2	922.9	1161.8	237.2	903.4	1137.0
Cd	21.1	72.5	66.7	21.1	72.5	66.7
Pb	82.0	134.6	142.3	77.6	127.4	134.7

* Twice this limit permitted on permenant grassland

The sludge additions to the experimental sites were therefore limited by the Zn equivalent.