HGCA

PROJECT REPORT No. 303

INTEGRATING MANURES, SLURRIES AND BIOSOLIDS AS NUTRIENT SOURCES IN ARABLE CROP ROTATIONS

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INTEGRATING MANURES, SLURRIES AND BIOSOLIDS AS NUTRIENT SOURCES IN ARABLE CROP ROTATIONS

by

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INTEGRATING MANURES, SLURRIES AND BIOSOLIDS AS NUTRIENT SOURCES IN ARABLE CROP ROTATIONS

COLLABORATIVE RESEARCH

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ABSTRACT

Without careful management, manures can cause loss of yield and quality as a result of both under- and over-fertilising. In addition to possible financial penalties, organic manures represent a major potential source of both point source and diffuse pollution. Better information is required to provide the agricultural industry with confidence in their use. Focused applications of manures can benefit crop yields. This project, therefore, focused on (a) a better quantification of the N mineralisation from dewatered sludge cake and composted products (i.e. materials from which fertiliser value was predominantly driven by organic N release) and (b) shifting applications of liquid manures (sludges and slurries) from autumn to spring, thereby increasing their N fertiliser value.

Three separate, but linked, activities formed the project so that understanding was obtained at all operational levels: detailed, small plot experiments, supporting laboratory experiments to further understand N release from the organic fraction of solid manures and a demonstration phase, scaling up on large (semi-field scale) plots, covering use, application techniques, crop effects and economic aspects.

The small plot experiments using the solid ('high dry matter') materials targeted single season and rotational aspects. These were undertaken at two sites over three years (Gleadthorpe, Nottinghamshire and Emley, Yorkshire). The N fertiliser replacement value (FRV, % of N applied), was not affected by manure application rate, but differed considerably between materials: 15% of the organic fraction in the first year for fresh dewatered cakes and 5% for composted materials. There were also substantial residual effects in the second and third years. Breakdown was related to thermal time. The data will be used to improve existing recommendation systems. The slow release N increased leaching in the second winter after application at large manure application rates (750 kg/ha N), because N continued to mineralise after crop uptake ceased. There was an indication that the slow release N also increased grain N content. Laboratory incubations were a good guide to whether the materials were likely to be 'slow' or 'quick' mineralisers.

The small plot experiments using liquids focused on seasonal aspects only, using sites only for one season. Experiments were undertaken on two sites per year for three years, i.e. six site-years (three sites each at Bridgets, Hampshire and Coven, Staffordshire). The experiments clearly demonstrated that liquid manures could be top-dressed to cereal crops, thus reducing the nitrate leaching risk and increasing their fertiliser value. Practically, there was a wide window of application, with similar responses from applications during early tillering through to stem extension. Fertiliser value was linearly related to the ammonium-N content of the liquid manures.

Three sites were successfully used to demonstrate principles of good fertiliser management at the semi-field scale (Bedale, N. Yorks and Coven, Staffs in 2000 and Sleaford, Lincs in 2002).

SUMMARY

Background and objectives

Common practice in the UK is for organic amendments (including farm manures and sewage sludges) to be applied to arable stubbles or fallow ground in the autumn-early winter period, prior to the establishment of the next crop. Without careful management, in addition to possible financial penalties, organic manures represent a major potential source of both point source and diffuse pollution. Different manures/sludges offer different challenges. Farmyard manures, sludge cakes and dry sludge products generally contain most N in an organic, slow release form. The effectiveness of this N source remains to be accurately quantified and understood, to develop reliable fertiliser recommendations. Liquid digested sludges and slurries provide a large proportion of N in a readily available, ammonium (NH_4-N) form. Focusing on spring applications decreases nitrate leaching risk. Top-dressing cereals with cattle or pig slurries or with liquid digested sludge, using suitable equipment, is an option that requires investigation, therefore.

The hypothesis that we tested in the project was that *by a better understanding of nitrogen release and loss pathways, as affected by application timing, type of manure and sludge, it is possible to better quantify N supply from these sources and to reduce inorganic N fertiliser inputs by, on average, 40 kg/ha to crops receiving organic manures.*

Other issues inevitably are raised by the use of sewage sludges on agricultural land: pathogens and metals. These concerns are equally applicable to the use of animal manures. Some measurements of these aspects were made within the project, though other research programmes are devoted to these particular issues in much more detail.

Project structure and methods

Three separate, but linked, activities formed the project so that understanding was obtained at all operational levels:

1. Detailed plot experiments:
    - Use of solid ('high dry matter') materials, targeting single season and rotational aspects - undertaken at two sites over three years (Gleadthorpe, Nottinghamshire and Emley, Yorkshire).
    - Use of liquids, covering seasonal aspects only, using sites only for one season - undertaken two sites per year for three years, i.e. six site-years (three sites each at Bridgets, Hampshire and Coven, Staffordshire).

2. Supporting laboratory experiments to further understand N release from the organic fraction of solid manures.
3. Demonstration phase, scaling up on large (semi-field scale) plots, covering use, application techniques, crop effects and economic aspects. Three sites were used (Bedale, N. Yorks and Coven, Staffs in 2000 and Sleaford, Lincs in 2002).

Plot experiments – solid manures

Five sewage sludges (dewatered cakes or cake products) and old, composted cattle FYM were applied at four application rates to separate plots in autumn 1998:

Code	Supplier	Works	Comments
YW1	Yorkshire Water	Esholt	Dewatered digested cake - some secondary treatment
YW2	Yorkshire Water	Dewsbury	‘Standard’ dewatered digested cake
YW3	Yorkshire Water	Lundwood	Some treatment/composting
ST1	Severn Trent Water	Mansfield	‘Standard’ dewatered digested cake
ST2	Severn Trent Water	Derby	‘Standard’ dewatered digested cake
FYM	ADAS	Gleadthorpe	Old: composted

Cereal crops, which received no additional N fertiliser, were then grown for the next three years to measure the longer-term N release from these materials. Also included in the experimental design was a fertiliser response curve, based on applications of ammonium nitrate, to allow calculation of the fertiliser value of the manure applications.

Application rate of each material was based on a target N loading - either a single dressing (in autumn 1998) of 250, 500 or 750 kg/ha N, or an annual application (in autumn 1998, 1999 and 2000) of 250 kg/ha N. The lowest application rate was based on the guidelines within Defra’s Water Code. Within this Code, biennial applications of up to 500 kg/ha N also allowed in some circumstances. This is not permitted in Nitrate Vulnerable Zones, however. The 750 kg/ha N treatment is outside current best practice but was included (a) to test the environmental effects of such a treatment and (b) to increase the likelihood of being able to track the fate of a single application over three years.

The two experimental sites offered contrasting soil textures for comparison. Gleadthorpe (Gt) is a typical sandland soil: very light and drought-prone, with low levels of organic matter. The second site at Emley (Em) is traditionally a grassland area due to the constraints of the rainfall. However, as a result of the large amounts of rainfall that the site receives, it can grow good cereal yields.

Plot experiments – liquid manures

Whereas the solid manure experiments focused on the longer-term release of N from the organic fraction, the aim of the liquid manure experiments was to study the much larger ammonium-N (NH_4-N) fraction. Therefore, a series of annual experiments was used, investigating the effects of top-dressing cereal crops. There were two sites in each year: Bridgets, a shallow silty clay loam over chalk and Hattons, a sandy loam to depth. The site supplied by Severn Trent Water (Hattons Farm: Ht) was the "core" site and so included detailed measurements of ammonia loss and nitrate leaching. The second site, at ADAS Bridgets (Br), included assessments only of crop yield and fertiliser N equivalent values of the manure applications. The sandy soil at Ht provided a useful test of leaching risk.

Each experimental site included the following treatments: Control, receiving no manure; Four liquid manures applied at four timings; Fertiliser response plots. Four organic manures were used in the experiment: pig slurry, cattle slurry, liquid digested sewage sludge (supplied by Yorkshire Water) and liquid digested sewage sludge (supplied by Severn Trent Water). The application rate of each material was based on a target N loading of 120-150 kg/ha total N. Application rates were based on a preliminary analysis of the material prior to spreading. There were four separate application timings:

1. October (Band spread, 30 cm spacing, after drilling);
2. GS 24/26 (Band spread, 30 cm spacing);
3. GS 30 (Band spread, 30 cm spacing);
4. GS 39 (Band spread, 30 cm spacing).

The same manures were used for all applications at both sites each year, by transporting a sufficient quantity to each site and storing it in covered tanks. The liquids were thoroughly stirred before application to ensure a homogenous material on each occasion. The liquids were applied with the ADAS precision plot applicator, which placed the manures on the soil surface in bands, about 30 cm apart. Application rate was based on an analysis of the manure pre-spreading (for total N).

Measurements

The following measurements were made on the small plot experiments:

• Topsoil analysis at experiment start:	Nutrients and metals
• Manure analysis at spreading:	Nutrients and metals
• Soil Nmin, soil mineral N(NO_3-N plus NH_4-N):	Spring and post-harvest
• NO_3-N leaching:	Autumn-applied manures
• NH_3-N volatilisation:	Liquid manures only
• Harvest data:	Grain & straw yield Grain & straw NPK Grain metals
• Topsoil analysis at experiment end:	Nutrients and metals (solids expt only)

Both the solid and liquid manure experiments were fully replicated (3 reps in randomised blocks), allowing statistical analysis.

Estimation of Fertiliser Replacement Value

In manure experiments investigating N fertiliser value, the fertiliser equivalence of the manure is commonly expressed as 'Fertiliser Replacement Value' (FRV). Another commonly used term, meaning the same, is 'N efficiency' of the manure. Fertiliser Replacement Value or N efficiency can be defined as the proportion of the manure's total N content that is equivalent to an application of inorganic N fertiliser (usually ammonium nitrate) applied according to best practice in the spring. So, if a manure has a FRV of 10%, this means that out of an application of, say, 250 kg/ha total N, it will supply to the crop an amount of N equivalent to 25 kg/ha N as ammonium nitrate fertiliser. Ammonium nitrate is taken as the standard for calculating FRV. Calculation of FRV needed inclusion of a fertiliser response curve in the experiment, and the approach includes an important assumption: that any yield benefit from the manure application is derived only from the N contained within that manure (i.e. not from other major or minor nutrients, nor from any added benefit of added organic matter). The approach works in most cases, including this project.

Laboratory studies

These were included to supplement the field studies. In years 1 and 2, samples of each manure were taken for aerobic (in a sandy soil at 60% Water Holding Capacity and 20 ^oC over 16 weeks) or anaerobic (35 ^oC for 1 week) incubation. Additionally, samples were sent to the ADAS laboratory for assessment by Near Infrared Spectroscopy. The intention was to determine if spectral peaks provided any information on N content and the 'mineralisability' of the N.

Demonstration sites

This was where application techniques and agronomic effects were demonstrated on a semi-field scale. These large, unreplicated plots were not intended to form part of the scientific experiments, but were designed to demonstrate an integrated approach to planning manure N use, in combination with fertiliser N. Yield mapping by both a GPS equipped combine harvester, or a grid sampling of the plots using the small plot combine, were attempted to aid critical assessments of the results from these sites. Sites were successfully completed in 2000, with over 100 visitors attending each site: Old Hatton Farm Staffs; Bedale Castle, North Yorks. The Foot and Mouth Disease outbreak of 2001 meant that proposed sites for that year had to be aborted. As a replacement event, demonstration plots were set up at the Cereals 2002 event in Sleaford.

Results: manure analysis and variability

Variability in manure analysis is often cited as a reason why farmers lack confidence in reducing fertiliser inputs after manure applications. Data confirmed that nutrient content could vary within a manure type. However, the mean values were remarkably similar to the values published in the industry standard reference book, RB209.

Whereas variability in N might be perceived as a large risk given a crop's typically large response to N inputs, there is much less risk associated with P and K input. Most arable soils are adequately supplied with P and K. At adequate levels of soil P and K, responses to fresh additions are unlikely, so that using standard manure nutrient values will be satisfactory. Combining this with periodic soil analysis (e.g. every 5 years) for standard nutrient content provides a further safety net. Thus, there is rarely a justification for not decreasing PK fertiliser inputs (often substantially) after manure/sludge applications.

Average nutrient content of each solid manure/sludge and comparison with 'standard values' taken as the industry norm and published in Anon. (2000). SE = standard error.

	DM (%)		Total N (kg/t)		P_2O_5 (kg/t)		K_2O (kg/t)		MgO (kg/t)		NH_4-N (kg/t)		NO_3-N (kg/t)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
RB209	**25**		**7.5**		**9**		**trace**		**1.3**		**nd**		**nd**	
YW1	28	1.1	7.1	0.67	8.4	0.73	1	0.09	1.1	0.08	0.4	0.19	0.1	0.08
YW2	24	1.0	8.3	0.49	7.3	0.45	0.6	0.05	1.6	0.12	1.2	0.21	0	0.01
YW3	36	2.3	10.1	0.89	11.3	0.7	1.1	0.11	2.4	0.25	0.2	0.11	0.5	0.17
ST1	22	1.2	10.1	0.31	9.3	0.25	0.4	0.03	2	0.04	2.2	0.28	0	0
ST2	28	1.2	9.8	0.31	13.2	0.75	0.6	0.04	2.3	0.07	1.8	0.12	0	0
RB209	**25**		**6**		**3.5**		**8**		**0.7**		**0.6-1.5***		**nd**	
FYM	40	4.2	5.9	0.24	3.5	0.39	10.7	1.37	3.4	0.78	0.1	0.04	0.3	0.14

* Depending on age & management; nd = not determined.

Average nutrient content of each liquid manure/sludge and comparison with 'standard values' taken as the industry norm and published in Anon. (2000). SE = standard error.

	DM (%)		Total N (kg/m^3)		P_2O_5 (kg/m^3)		K_2O (kg/m^3)		NH_4-N (kg/m^3)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Cattle slurry	6.3	0.25	3.2	0.10	1.3	0.04	3.3	0.19	1.6	0.07
RB209	6.0		3.0		1.2		3.5		1.5	
Pig slurry	3.7	0.29	4.2	0.24	2.1	0.11	3.7	0.17	2.7	0.12
RB209	4.0		4.0		2.0		2.5		2.4	
Liquid DS1	3.8	0.11	2.7	0.10	2.1	0.15	0.3	0.04	0.9	0.04
Liquid DS2	2.4	0.18	1.8	0.07	0.7	0.07	0.3	0.03	0.9	0.02
RB209	4.0		2.0		1.5		trace		1.0	

Because of the extent of crop response to under- or over-supply and the mobility of nitrate, N is seen as the high-risk nutrient and the main issue for risk management. Whereas the standard value approach is satisfactory for P and K, it is less useful for N given the crop's likely responsiveness to this nutrient. Variability therefore has potential to cause problems in nutrient management at the farm level, but there are approaches that can be used to manage this variability:

- Laboratory analysis of manure – Periodic analysis is likely to give a better assessment of manure or sludge nutrient content, with most of the variation from the average nutrient content explained by addition or exclusion of water and, hence, dilution or otherwise of slurry or sludge, or moisture content of solid manures/dewatered cakes. Water Companies may have an advantage here because they all provide analysis of sludge products on a routine basis. Whilst qualities from individual sources are relatively stable, there are treatment centre differences.
- On-farm analysis – methods have been available for some time for liquid manures and it perhaps these manures, with a high proportion of readily available N, where the test is of most value. This method was successfully used at the demonstration sites for assessment of N content.

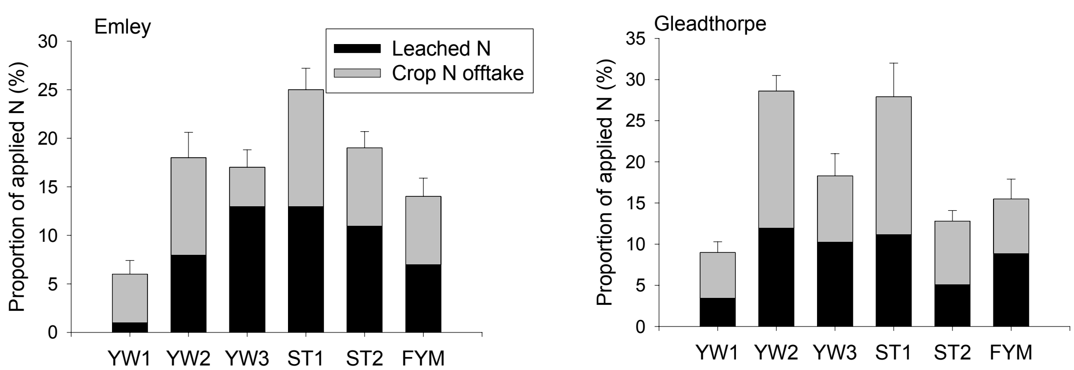
The project showed that, in some circumstances, nitrate can contribute to the fertiliser value of these solid manures. The presence of nitrate is associated with aerobic conditions (usually composting), and not normally with farm manures managed and stored in conventional ways. Consequently, it has not been a part of the routine suite of analyses, given that only trace amounts have been detected in the past. There was evidence in the old, composted FYM used in this project and the composted sludge cakes that nitrate can be a significant proportion of the readily available N fraction. Its analysis therefore ideally needs to be included as a routine.

Results: Nitrogen partitioning between soil and crop, nitrogen balances

The upper application rate of 750 kg/ha N for the solid manures was above any rate recommended in existing Codes of Practice, but it was included to allow tracking of the applied N over three years. The Figure shows the partitioning between N removed from the field in harvested crop and that leached from the soil over three winters. Further calculation and statistical analysis showed that application rate had no significant effect on the proportion of the applied N that was allocated to each pathway.

Allowing for the background 'control' contribution, 70-90% of the applied N remained in the soil after three years. This has important implications for soil fertility. There was, however, a significant manure type effect, which could be explained by understanding the manure characteristics. Largest removals were from the two 'fresh' sludge cakes (YW2 and ST1) because these had a larger proportion of readily available N (i.e. ammonium-N), which could be leached and/or used by the crop. The composted manures, with most of the N bound in recalcitrant forms, contributed most to the soil organic N pool. Although the composted dewatered cake YW3 would have provided a large recalcitrant organic matter pool, it also contained substantial nitrate that was leached.

These results have important implications for soil quality. Further work is required on the potential benefits of composted materials, because much of the readily decomposable organic matter would have undergone degradation in the compost heap before application to the soil.



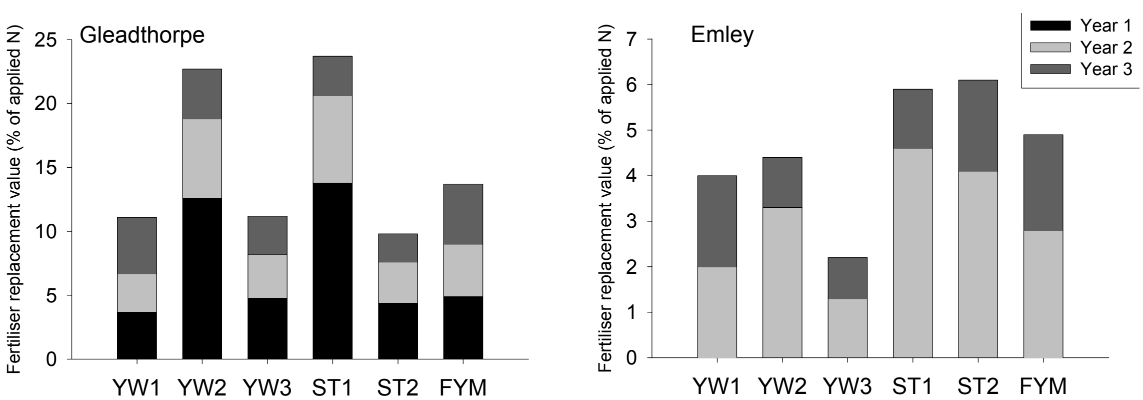
Proportion of N removed by leaching and crop off-take (% of N applied in FYM/sludge cakes) as a total of three years for the Gt and Em sites. Error bars denote standard errors.

Results: Fertiliser replacement value (FRV)

Solid manures

The full three years of calculated FRVs were available for Gt, but the first year was missing from the Em site (poor crop establishment), and are shown in the Figure. An analysis of variance allowed us to find the main factors that affected FRV. These analyses were undertaken excluding the annual fresh application, and therefore relate to first year and residual effects. The following conclusions could be drawn about the main factors. The statistics were more robust for the Gt site, because this included data from all three years, whereas Em did not include year 1:

- Year – a highly significant effect (P=0.003 Gt or 0.04, Em) of application year on FRV, with the effect generally diminishing each year after application for the 'standard' sewage sludge cakes. However, there was also a year x manure interaction (P<0.001). This is because, particularly the composted manures, showed a fairly level FRV in each of the three years.
- Manure Type – as would be expected, different manures showed highly significantly different sizes of FRV (P<0.001), with the 'standard' sewage sludge products having a larger FRV, particularly in the first year.
- Manure rate – no effect. The FRV (calculated as a proportion of applied N) was not affected by application rate. This is good, as it shows that the effect is a linear one. Within the range of N rates tested, doubling the application rate, for example, would also double the fertiliser value (in kg/ha).



Summary of the FRV (% of applied N) for each manure/sludge over three years (Gt), and years 2 and 3 (Em).

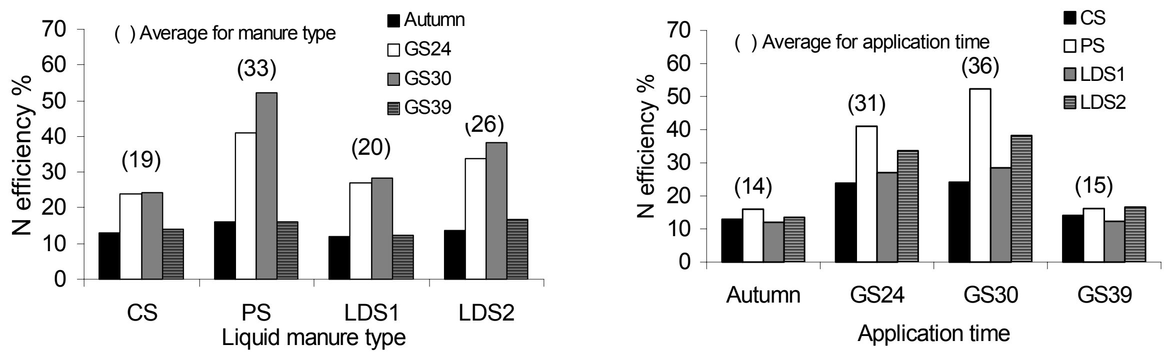
Thus, in summary, the FRV of the organic materials could be split into 2 groups depending on the material type:

- 'Fresh' dewatered cakes and manures – larger FRV in the first year after application, with a diminishing return of about 50% of year 1 in year 2 and 50% of year 2 in year 3.
- 'Composted' materials - with a smaller FRV in year 1, but with a similar value in all three years.

Liquid manures

Yields following application at GS24 and GS30 were elevated significantly ($P<0.001$) above those from autumn or GS39 treatment. Effects of manure type were less consistent but significant ($P<0.05$) in 4 out of 6 site-years.

(a) Manure type and application time (b) Application time and manure type



Nitrogen efficiency (FRV) of liquid manures compared to spring applied fertiliser N for grain yield, averages for the manures across the six site-years of data, 1998/99-2000/01, at Hattons and Bridgets

Consequently, highly significant differences ($P<0.001$) in FRV were apparent in 5 out of 6 site-years and, again in 4 out of 6 site-years there were differences ($P<0.01$) in FRV according to manure type, with pig slurry generally giving the highest efficiencies. The effect of application timing was consistent across all manure types and FRV for all manure types was similar following both autumn and late spring (GS39) applications. Although there was a trend towards increasing FRV with GS30 applications compared with GS24, differences reached statistical significance ($P<0.001$) only at Bridgets in 1999/00 and 2000/01 and this trend was actually reversed at Hattons ($P<0.001$) in 1999/00.

Factors affecting FRV

FRV depends principally on the following elements:

Crop N supply = NH_4-N content – N volatilised – N leached + organic N mineralised

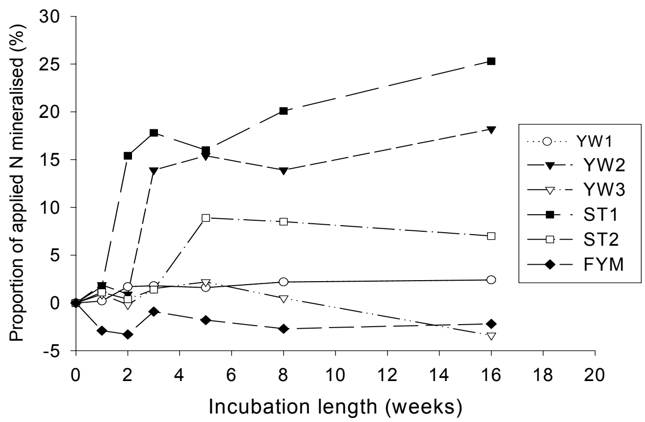
The NH_4-N content represents the 'readily available N' fraction. The above scheme explains the rationale of the project. For liquid manures, with a large readily available N component, the aim is to minimise losses by leaching and volatilisation. For solid manures (excluding poultry), the emphasis had to be on understanding mineralisation of the organic fraction and optimising application timing. The above framework also demonstrates that all of the above factors need to be understood and quantified in order to develop a reliable recommendation system.

For solid manures, statistical analysis showed that the following factors affected the FRV: year and manure type. There was also a year x type interaction. Rate had no effect on the FRV, expressed as a proportion of the N applied (but, obviously would have an effect in terms of absolute amounts). For the solid manures, we did not examine time or application, or speed and method of incorporation. Given the available resources within the project, the aim was to focus on autumn applications and on the organic fraction. Indeed, because these materials are not appropriate for top-dressing the growing crop (other than grass), then the most often used strategy for solid manures is ploughing down in the autumn. However, using the MANNER model, adjusted for more appropriate mineralisation factors for each manure type (see later), it was possible to examine the effects of decreasing nitrate leaching and ammonia losses on the total FRV. These calculations showed that, for composted manures with a low ammonium-N content, there was little benefit of adopting techniques that reduced losses (e.g. YW3, FYM and, to a lesser extent, YW1). The greatest benefits were with the fresh manures with a larger ammonium content, as would be expected. Then, there was clearly an advantage in decreasing losses. Note that this calculation did not include consideration of nitrate. If the composted manures contained significant nitrate, then delaying application of the manure needed to be considered, to decrease leaching of this component.

For liquid manures, only a limited range of factors likely to affect FRV could be studied within the project. As anticipated, application time had a major impact on FRV, with the highest manure N efficiency (for all manure types) consistently recorded following applications at GS 24 and GS30 ($P<0.001$).

Mineralisation impact for nutrient supply

The organic N fraction of manure has been considered as comprising several pools, relating to the ease of breakdown. The 'true' organic fraction is often considered as following a curvilinear or two straight line degradation, being driven by temperature (thermal time). This corresponds to a rapid degradation of the easily decomposable fraction followed by a more gradual mineralisation of the more recalcitrant fraction. This classic pattern was seen for the dewatered cakes YW2 and ST1 during the aerobic incubations. However, this same pattern was not noted for the composted materials, particularly YW1, YW3 and FYM. It could be argued that this is because the readily degradable component has been broken down during composting, leaving only a more recalcitrant fraction for degradation on application to the soil. The incubation studies were therefore a useful indicator of the likely performance of the materials on application to the soil. On the basis of the limited number of observations within this project, NIRS was not a good predictor of mineralisation potential.



Change in mineralised N with time, expressed as a proportion of the N applied in manures/sludges: second incubation series (2000).

Prediction: MANNER and other recommendation system comparisons

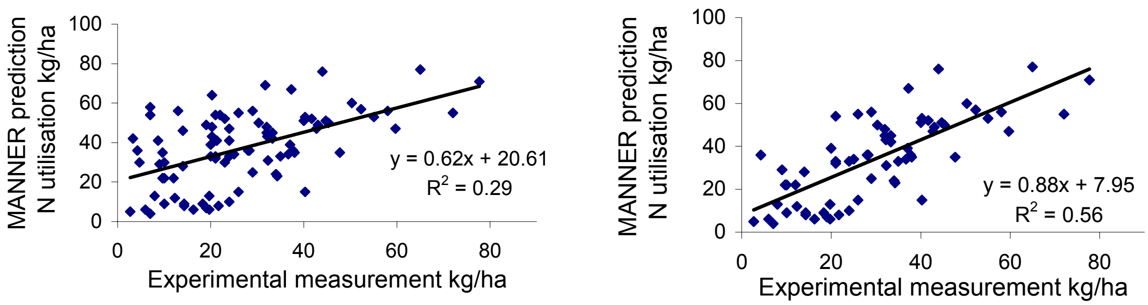
It is accepted that, to date, a weakness in the MANNER recommendation system has been in the N mineralisation component of the model, taken as 10% of the organic fraction being crop available and derived from relatively few empirically based field observations. Whereas, this has proved satisfactory as a first approximation, a Defra-funded research programme has just been completed to improve this aspect (NT2106). Data from this SAPPIO project provided information on dewatered sludge cakes and composted materials that were not included in the Defra-funded project.

Two approaches were therefore adopted to estimate mineralisation of the organic component:

- First, the MANNER algorithms were assembled on an Excel spreadsheet, allowing adjustment of the mineralisation factor from 10% of the organic component being available. It was assumed that the leaching and volatilisation components were valid, and the organic component was adjusted to provide best fit to the data.
- Secondly, the revised mineralisation algorithms from the Defra-funded project were compared with our measurements of N release from this project.

Using these approaches, it was concluded that two N release factors should be applied to the materials used in the project: 15% for fresh dewatered cakes and 5% for composted cakes and manures). We were unable to compare measured FRVs in the second and third years against recommendations because, currently, recommendation systems do not take account of residual effects. However, there is a current Defra-funded project that is developing a longer-term soil N accounting model (SNSCAL, E. Lord, Pers. Comm), where the data will be used.

(a) All manures, applications aut, GS24, 30, 39 (b) All manures, excluding applications GS39



Comparison of experimentally measured liquid manure N fertiliser replacement value (FRV) and MANNER predicted FRV.

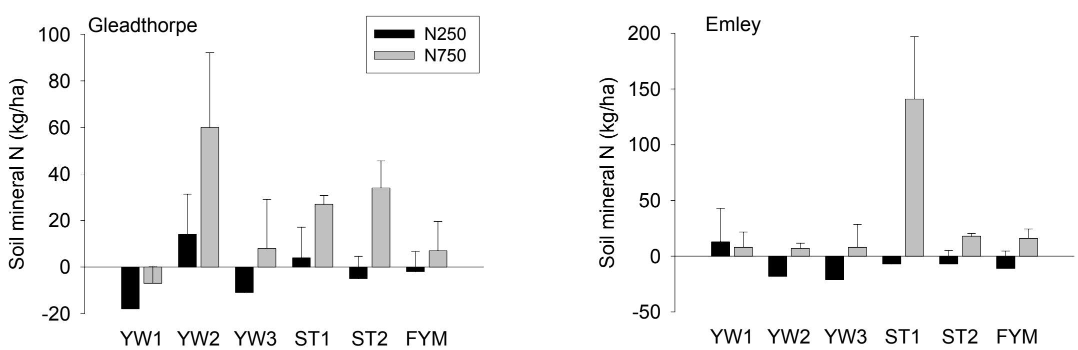
For the liquid manures, the results followed the expected pattern, with the measured %FRV reflecting the analyses of the manures and the time of application. The Figure above shows the results of the MANNER predicted FRV for the liquid manures compared with experimentally measured values. Where the results over the 3 years for all manures, across all application timings are compared with MANNER predictions, the correlation was poor. This was not surprising since FRV of the later (GS39) applications was relatively low, the manure N applied at this time being known from earlier research to be associated with lower efficiency and also some risk of foliar scorch. However, MANNER is not currently equipped to deal with such scenarios. Where comparisons of the MANNER predictions were restricted to autumn, and the earlier spring timings, the correlation with field measurements was encouraging, giving further confidence in the use of MANNER to provide guidance on manure N replacement values.

Results: Environmental Issues

N losses

The results confirmed some differences in leaching risk between materials (i.e. between the liquid and solid manures tested), although the data were not as conclusive as shown by other work. Although subsequent leaching losses are driven by the amount of rain after application, rather than calendar date, nitrate losses were surprisingly small at the Hattons site following slurry and liquid digested sludge applications in mid-November. However, applications were left on the surface, which would have had two effects: first, some N would be lost as ammonia, thus decreasing the amount available for leaching. Secondly, the nitrate would have further to travel before being lost from the rooting zone (compared, for example, with burial at depth by ploughing). Such conflicts in emissions via different N flux pathways are becoming more of an issue, because it is not acceptable to decrease N losses to the environment via one route, while increasing them by another (so called ‘pollution swapping’). Our data on nitrate losses from the dewatered cakes and FYM show several important points when considering nitrate policy:

- There is a small risk with manures containing a small proportion of readily available N, which confirms current policy. However, as discussed above, there is an issue with high nitrate contents in composted manures. We measured substantial nitrate losses from manures/composted sludges that contained nitrate. This is not currently accounted for but is a potential risk, if composting increases as a method of recycling materials to agricultural land.
- Application rate is important. Defra's Water Code suggests that biennial applications of low available N manures at a nitrogen rate of 500 kg/ha are acceptable (except in NVZs). Our data would support this. The approach has advantages, not only to Water Companies in their sludge spreading but, also, for farmers with FYM, because the restriction to lower application rates, over a wider area, effectively increases the operational costs of spreading. However, limits within NVZs are smaller: an annual maximum of 250 kg/ha N on individual fields, but limits averaged over the farm area of 210 kg/ha N for arable and 250 kg/ha N for grassland (including grazing returns). Our data suggest that the 500 kg/ha N rate would still be acceptable. A rate of 750 kg/ha N was also included in the project, but we can conclude that this is too large to keep nitrate leaching losses from autumn applications within acceptable limits. It also has consequences for nitrate leaching in the following winter – see below.
- There was a large leaching effect from the 'fresh' dewatered cakes in the following winter after application (i.e. after the first harvest, Figure below) at the highest application rates. This was probably due to continued N release after the crop had started to senesce. Thus, the implications of policies in the following year also have to be considered.



Post harvest soil mineral N at Gt (0-90 cm) and Em (0-60 cm), after harvest 1999, i.e. in the second autumn after application. Manure/sludges applied at two rates: 250 and 750 kg/ha N. Error bars denote standard errors.

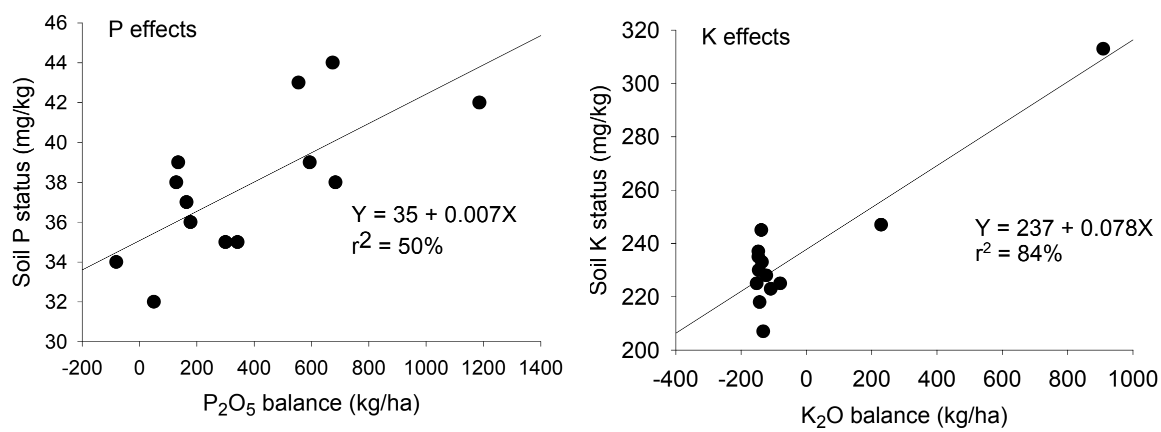
Ammonia losses, following application of the liquid manures, were measured at the Hattons site (for GS 24 and GS30 applications only) using passive diffusion samplers, commonly known as dynamic chambers. The measurements were too few and generally too variable to draw any firm conclusions, although it could be seen that cumulative losses from sludges, for which there are few data, followed a pattern very similar those from other manure types and were well described by a Michaelis-Menten function. Losses from the liquid sludges tended to be lower than from the slurries, possibly as a result of their lower solids contents, though differences reached significance on one occasion only ($P<0.05$, GS30, 2000).

Metals

It was not the aim of this project to examine in great detail the issues of heavy metal contamination from manures/sludges. Grain concentrations of all metals were well within safe limits following sludge applications, even though we were testing a 'worst case' situation: i.e. applications of sludge/manure in the absence of additional fertiliser N. In practice, fertiliser N would be applied in addition to the manure/sludge. The extra yield resulting from the fertiliser would dilute grain metal concentrations still further. Therefore, even though we did not use fertiliser practices that would dilute grain metal concentrations, we still did not see problems.

P effects

Analysis of the manures/sludges confirmed that they were valuable sources of P, and that the manures also contain substantial K. Data from the Emley site allow an examination of the effect of manure/sludge additions on soil PK status. This was not possible at Gleadthorpe because some plots received addition PK fertilisers and no trends were therefore obvious.



Emley: relationship between nutrient balance over three years and change in soil nutrient status.

The spread of data points for soil K was less than with P because all of the sludges contained only trace levels of K, and the relationship is greatly influenced by the K supply from the two FYM rates that were monitored. Results therefore have to be treated with caution, but the Figure above shows the relationship between soil K status and K balance over three years for plots that received nil, 250N or 750N manure/sludge applications. The slope of the line (0.08) equates to a positive balance of about

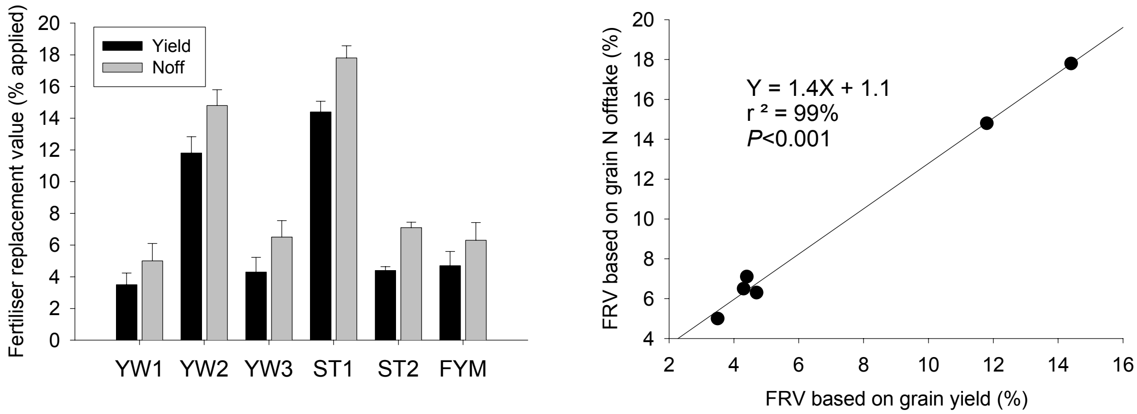
600 kg/ha K_2O to raise soil K status by 50 mg/l. Although the K trends are unduly influenced by the FYM treatments and it would be unwise to draw strong conclusions from these data in isolation, this relationship agrees well with other experiments, which have demonstrated a balance of 400-600 kg/ha K_2O to raise soil status by 50 mg/l extractable K. The slow change in soil K status with K balance supports the approach of using standard values of manure K content in fertiliser planning. A similar linear relation ship was noted with P, above. Typically, the slope of this line is 0.02-0.03, which translates to the need for a positive balance of 400-600 kg/ha P_2O_5 to raise the soil P status by 10 mg/l. The practical outcome of this is that it takes a long period of over- or under-fertilising to impact on soil P status. This should provide further evidence for the safety of the approach of using standard nutrient figures when reducing fertiliser inputs after manure applications (as discussed earlier). Interestingly, the slope of the relationship for these Emley data was *c.* 0.007, which is equivalent to >1000 kg/ha P_2O_5 applied to raise the soil P status by 10 mg/l.

A problem of regular manure applications to a single field is the imbalance between the N:P ratio of the manure/sludge and the crop. The ratio of nitrogen to phosphate was, on average, about 1:1 for dewatered cakes and 1.5-2.5:1 for manures and liquid digested sludges. This compares with a ratio of about 7-11:1 for most cropping situations. Consequently, even though annual manure/sludge applications would be permissible under current NVZ legislation, this would lead to a build up of P (and, for animal manures, K) in the soil, with possible adverse environmental effects for surface waters in the event of erosion or surface run-off to nearby streams/rivers.

Results: Economics

Fertiliser savings

Savings from manures are usually calculated in terms of NPK fertiliser replacement values. However, it should also be remembered that these materials are valuable sources of other nutrients. Sulphur deficiency of crops is increasing and manures are a useful source of S. Many farmers also value the organic matter, though it is difficult to place a financial value on this. Based on the measured nutrient contents of the manures and the measured nutrient availability, the value of an application at a rate to supply 250 kg/ha N was in the range £83/ha (LDS) to £150/ha (FYM). Most of the savings come from reduced PK inputs. Thus, our starting hypothesis that savings of £80/ha can be made is sound. However, these do not take account of the spreading costs. The importance of correctly accounting for manure N is not only in fertiliser value, but also in environmental effects – over application increases nitrate leaching after harvest. There are also potential quality effects on crop produce related to N applications.



Histogram: comparison of Fertiliser Replacement Value (FRV) calculated from yield and grain N off-take (with standard errors). Line graph: relationship between FRV calculated from yield and grain N off-take.

Yield and quality

Data from the Gt site showed an indication of a benefit to grain N concentrations in the first harvest after application of the manure/sludges (data shown above). This might be expected, due to slow release N from the organic materials. If N is released during the grain filling period this might therefore benefit grain protein levels. The experiment was not designed specifically to test for this effect, so the method for observing the effect was indirect and only at one site in one year (no data for Emley in the first year after application). FRV was calculated from both yield response and grain N off-take (Figure, below).

For all manure/sludges, FRV calculated from grain N off-take was larger than when calculated by yield. A paired t-test showed the difference to be highly significant. A regression analysis shows that FRV(N off-take) was about 20% greater than FRV(yield). This suggests continued N uptake into the grain-filling phase, which warrants further examination in more detailed experiments.

Risk and risk management

Fertiliser usage statistics suggest that many farmers are averse to risk when planning fertiliser use after manure/sludge applications. The project suggests that the risk of yield loss from reducing P and K inputs after manure is very small, and we hypothesise that most of the perceived risk is from under-fertilising with N given the crop's likely large response to this nutrient.

The main source of risk to the farmer is loss of yield and quality from under- or over-fertilising following manure applications, brought about due to:

- Variability in manure N content;

- Uneven spreading of manure.

Some of this risk is immediately reduced by adopting a manuring strategy that aims to supply no more than half of the crop's need from manure application. In practice, following the Water Code or NVZ regulations ensures this for most crops by limiting the total N application from manure that can be applied in one year. Data from this project allowed a quantification of the first risk (i.e. variability in nutrient content). To test this, we examined the nutrient analyses to find maximum and minimum N contents for cattle slurry, cattle FYM, liquid digested sludge and dewatered sludge cake, and compared these with standard values from RB209. The following assumptions were then made:

- Liquid manures applied 1 March at 50 m^3/ha to a loamy sand;
- Solid manures applied at 30 t/ha on 1 October to a loamy sand.

The MANNER model was then run to allow estimation of fertiliser N values for each of the manures, summarised below.

Estimated effects on N supply for selected manures of using 'standard' figures for N content and the range of N content values in this project. Liquids applied at 50 m^3 in spring and solid manures applied at 30 t/ha in autumn.

Manure	Range of N content	Total N (kg/ha)	Nleached (kg/ha)	Nvolat (kg/ha)	N supply (kg/ha)
Cattle slurry	minimum	95	0	6	53
	RB209	150	0	16	66
	maximum	195	0	30	80
LDS	minimum	32	0	2	29
	RB209	100	0	9	55
	maximum	190	0	11	62
Cattle FYM	minimum	150	2	0	15
	RB209	180	14	3	16
	maximum	182	2	0	19
Dewatered Cake	minimum	201	26	6	17
	RB209	225	26	6	20
	maximum	315	75	17	24

In this example, the imprecision in N supply as a result of variability in nutrient content can therefore be seen to approximate to a range of +/- 20 kg/ha N for liquid manures and +/- 10 kg/ha N for solid manures. Thus, the risk of over- or under-fertilising is small in practice. Using the yield response curve from, for example, Gleadthorpe 1999 the yield penalty from under- or over-fertilising was then calculated, compared with fertilising at the optimum rate. The range was a yield loss of 0.22 t/ha from under-fertilising by 30 kg/ha N, and a yield increase by over-fertilising by 30 kg/ha N. This is an important conclusion: by taking full allowance of the N fertiliser value of a manure application, even using standard data for manure N composition, the risk of yield loss is relatively small.

However, the real risk to the farmer comes from <u>not</u> making an allowance for the manure N applied, or only a small allowance. Obviously this risk increases if the manure in question is a manure with a high proportion of available N, such as a slurry or a liquid digested sludge (or poultry manure). For example, cattle slurry applied according to our scenario provides a fertiliser value of 66 kg/ha N. If a farmer only makes an allowance of, say, 16 kg/ha (the typical allowance from annual statistics on fertiliser usage), then there is a potential for over-fertilising by 50 kg/ha N compared with fertilising in the absence of manure. The yield and quality losses from this practice will depend on how well the crop stands, but data suggests that yield losses could be 0.5-1.0 t/ha, plus losses to quality associated with lodging.

So, again, the conclusion is important: the losses (in terms of quality and yield) from not taking full account of the N supply following an application of manure (particularly a liquid manure or poultry manure) are potentially larger than those likely to arise as a consequence of any imprecision associated with following the recommended practices as published in, for example, RB209.

It is also possible to estimate the environmental effects of over-fertilising by 50 kg/ha N. Numerous workers have now reported the upturn in nitrate leaching losses if N applications exceed the crop's optimum requirement. Leaching losses with incremental N applications follow a broken stick model, with only small increases up to the optimum (a slope on this line of about 5% for cereals), and then a large upturn after the optimum (a slope of *c.* 75%). Consequently, over-fertilising by 50 kg/ha N could increase leaching by 40 kg/ha N.

Again, this is an important conclusion: it is often thought that the main risk of nitrate leaching from manures coincides with the winter of their application. However, a major source of leaching loss can occur in the following winter and derives from over-fertilising the crop.

Recommendations

1. The project has shown that top-dressing of liquid manures on to growing cereal crops in the spring is a useful technique that could be adopted more widely. This is particularly relevant to farm slurries, and the options and opportunities need to be promoted more widely.
2. Poultry manures offer the advantage of a large proportion of readily available N. Small plot experiments have shown that this can be top-dressed, but there is a lack of suitable commercial equipment capable of applying sufficiently low rates for compliance with the NVZ regulations that are compatible with 12 m wide tramline systems, which is currently beyond the performance of the current generation of solids spreaders.
3. We have gathered considerable information on the N mineralisation dynamics of a range of organic materials. Whereas we now have 'rule of thumb' mineralisation factors for these materials, the data have to be incorporated into recommendation systems if they are to be used across a range of cropping and soil-type conditions. Two separate initiatives are underway (MANNER-NPK and SNSCAL) where the information will be used to refine fertiliser recommendation systems.
4. The project has shown that nitrate can form a substantial proportion of the readily available N fraction of composted manures. This is currently not accounted for in recommendation systems but needs to be included when the recommendation systems are next reviewed.
5. Water Companies analyse sludge as a routine. This offers potential advantages when calculating a fertiliser value, but the following steps need to be introduced to make full use of this information:
    - Ideally include ammonium-N and nitrate-N in the analysis suite;

- Link to a reliable recommendation system to provide an estimate of nutrient value of the sludge. This could be MANNER, after updating the mineralisation algorithms.

6. The potential effects of organic manures on grain protein levels warrants further examination.

7. NIRS offers potential as a rapid method of total N determination but relies on building a sufficiently large dataset to allow correlation between wet chemistry methods and spectra.

TECHNICAL REPORT

1. BACKGROUND

The agricultural industry does not optimise the use of nutrient inputs from manure sources. Common practice in the UK is for organic amendments (including farm manures and sewage sludges) to be applied to arable stubbles or fallow ground in the autumn and early winter period, prior to the establishment of the next crop. Even following high rate applications, the nutrient contribution, particularly nitrogen (N), to the following crops tends to be ignored because of (a) perceived losses over the winter period and (b) difficulty in assessing the N contribution from the manure, particularly from the organic fraction of solid manures. Annual fertiliser statistics consistently confirm the lack of nutrient attribution given to manures by farmers (Smith & Chambers, 1993). The resultant nutrient excess following 'bagged' fertiliser additions is not only wasteful, unnecessarily increasing input costs, but may give rise to further economic losses (e.g. due to crop lodging and adverse effects on crop quality: Hayward *et al*., 1993). Without careful management, in addition to possible financial penalties, organic manures represent a major potential source of both point source and diffuse pollution.

Knowing nitrogen content and form in manures, sewage sludges and sludge products is therefore central to devising land application strategies that (a) provide maximum fertiliser value for the farmer and (b) result in minimal environmental impact. This latter point is particularly important because of legislative controls on nitrate in water, as well as concern and pending legislation on ammonia emissions from agriculture.

Different manures and sludge materials offer different challenges. Farmyard manures, sludge cakes and dry sludge products generally contain most N in an organic, slow release form. Liquids contain a large proportion of ammonium N, with a more immediate risk of losses to the environment. The different materials are therefore likely to require different application strategies in order to minimise potentially harmful emissions.

Because liquid digested sludges provide a substantial proportion of N in a readily available, ammonium (NH_4-N) form, these require management strategies that will reduce the environmental risk posed by the applied NH_4-N by maximising crop utilisation. Shifting applications away from autumn stubbles to the spring can decrease nitrate leaching losses from the applied liquid manures to close to zero (Beckwith *et al.,* 1998). Top-dressing cereals with cattle or pig slurries or with liquid digested sludge, using suitable equipment, is an option that requires investigation, therefore.

With FYM and dewatered sludge cakes, most of the N content is in organic forms and there is the problem of assessing effective N supply from this organic fraction. Sludges are often thought of as providing a more ‘recalcitrant’ form of organic N. However, previous research suggests that supply can be quite variable with much depending on sludge source (Smith *et al*., 1992). Thus, the effectiveness of this N source remains to be accurately quantified, and the variation needs to be understood and accounted for in the development of robust fertiliser recommendations. Moreover, the release of organic N in the winter following autumn application needs further investigation to assess leaching risk.

The aim of this research was therefore to develop a strategy to allow farmers to more consistently and confidently reduce fertiliser nutrient, especially N, inputs in response to the application of animal manures and water industry sludges.

Other issues inevitably are raised by the use of sewage sludges on agricultural land: pathogens and metals. In fact, these concerns are equally applicable to the use of animal manures. Defra and others, including the Food Standards Agency (FSA) and UK Water Industry Research (UKWIR), are currently funding large research programmes to assess the validity of these concerns. However, as a subsidiary part of this project, some assessment was also made of the metal contribution to the soil crop system from the applications of manures and sludges. There are also other issues regarding the use of organic amendments in agriculture, which impact on sustainability. Firstly, ammonia losses following land application of organic manures are estimated at 34% of the total emissions (240 kt NH_3-N p.a.) from UK agriculture (Misselbrook *et al*., 2001) and represent a loss of nutrient value as well as an environmental threat. This needs to be more accurately quantified and techniques to minimise losses need to be developed. Secondly, the amendments are sources of phosphorus (P), as well as N, and use of this nutrient also needs improvement to encourage careful recycling and minimised pollution risk. Therefore, some measurements of these aspects were made within the project though, as with metals, whole Defra-funded research programmes are devoted to these particular problems.

2. OBJECTIVES

The hypothesis that we tested was that *by a better understanding of nitrogen release and loss pathways, as affected by application timing, type of manure and sludge, it is possible to better quantify N supply from these sources and to reduce inorganic N fertiliser inputs by, on average, 40 kg/ha to crops receiving organic manures.*

Detailed objectives

1) To optimise application timing and method for the spring dressings of liquid manures in arable crop rotations (in terms of crop yield and quality).
2) To measure and minimise nutrient losses to the environment (mainly nitrate leaching or ammonia emissions), associated with a spring application strategy for manures.
3) To quantify, and so make better allowance in fertiliser planning for, the nitrogen supply from the organic N fraction of sludges and manures, over a 2-3 year period following application.
4) To measure nitrate loss and so determine 'safe' application rates, in terms of leaching, from applications of predominantly organic N sources.
5) To evaluate and, if necessary, revise current N recommendation systems (e.g. MANNER) following sludge applications.
6) To make an economic appraisal of the techniques and strategies tested in the project.
7) To demonstrate components of the strategies identified from the detailed studies and from other work, at a semi-field scale.
8) To promote the results to the agricultural industry and the public.
9) To evaluate some aspects of soil sustainability (metal and phosphorus inputs), associated with the land application both of sludges and manures.

To test this hypothesis, the project was divided into 3 phases:

1. Use of solid ('high dry matter') materials, targeting single season and rotational aspects - undertaken on experiment plots; Use of liquids, covering seasonal aspects only - undertaken on experiment plots.
2. Supporting laboratory experiments to further understand N release from the organic fraction of solid manures.
3. Demonstration phase, scaling up on large (semi-field scale) plots, covering use, application techniques, crop effects and economic aspects.

3. PROJECT MANAGEMENT

ADAS was the research contractor and so was responsible for the day-to-day management of the project's fieldwork. ADAS reported to the Project Steering Group at 6-monthly intervals, comprising representatives of the main funders and the research contractor:

STW	Dr Chris Rowlands (Project Steering Group Chairman)
Defra	Mr Robert Cook (SAPPIO LINK Co-ordinator)[1] Dr Diana Wilkins (Policy Group)[2] Prof. Keith Syers (Project Assessor)[3]
HGCA	Dr Shona Campbell/Dr Claire Kelly
YW	Mr Ian Fairless
EA	Dr Nina Sweet/Mr Steve Woods
Tramspread	Mr Terry Baker
ADAS	Dr Mark Shepherd/Mr Ken Smith

Re-organisational changes meant that there were changes in personnel:

[1] Prof. Peter Street

[2] Dr Judith Stuart/Dr Iain Williams

[3] Prof. Peter Gregory

In addition to reporting to the Project Steering Group, annual written reports were provided in the required formats for HGCA and LINK. An annual presentation of progress was also made to the HGCA Committee.

4. MATERIALS AND METHODS

4.1. Project Structure

Three separate, but linked, activities formed the project so that understanding was obtained at all operational levels:

- Use of solid ('high dry matter') materials, targeting single season and rotational aspects - undertaken on experiment plots; Use of liquids, covering seasonal aspects only - undertaken on experiment plots (Fig. 1).
- Supporting laboratory experiments to further understand N release form the organic fraction of solid manures.
- Demonstration phase, scaling up on large (semi-field scale) plots, covering use, application techniques, crop effects and economic aspects (Fig. 1).

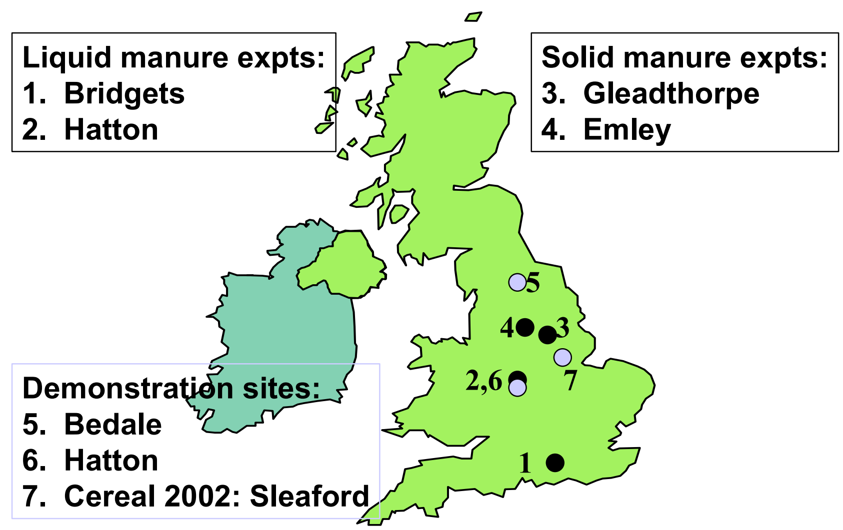


Figure 1. Location of the sites used within the project.

4.2. Small Plot Experiments

4.2.1 Solid manures

This experiment used two sites, on which cattle FYM and five sewage sludges were applied at four application rates to separate plots in autumn 1998. Cereal crops, which received no additional N fertiliser, were then grown for the next three years to measure the longer-term N release from these materials. Also included in the experiment design was a fertiliser response curve, based on applications of ammonium nitrate, to allow calculation of the fertiliser value of the manure applications.

Sites

The two experimental sites (Table 1) offered contrasting soil textures for comparison. Gleadthorpe (Gt) is a typical sandland soil: very light and drought-prone, with low levels of organic matter. The second site at Emley (Em) is traditionally a grassland area due to the constraints of the rainfall. However, as a result of the large amounts of rainfall that the site receives, it can grow good cereal yields.

Table 1. Site details for the solid manure experimental sites.

Location:	ADAS, Gleadthorpe Research Centre, Notts.	Woolrow Farm, Huddersfield, West Yorks.
Grid reference:	SK 597 706	SE 222 128
Abbreviation:	Gt	Em
Soil description:	Loamy medium sand over medium sand	Sandy silt loam over shale to varying depth (70-90 cm)
Soil series:	Cuckney	Rivington
Annual average rainfall:	650 mm	830 mm

Experiment design and statistical analysis

Each experimental site comprised of the following treatments:

- Control, receiving no manure;
- Six manures applied at four rates;
- Fertiliser response plots.

There were three replicates of each treatment. Each site therefore comprised of 111 plots, made up of the following:

	No. of treatments	No. of plots
un-manured control	1	3
6 manures x 4 application rates	24	72
fertiliser response plots (used years 1 and 3)	6	18
fertiliser response plots (used year 2)	6	18
TOTAL	**37**	**111**

Each plot was 5 m x 18 m (Gt) or 5 m x 15 m (Em).

Statistical analysis was based on two-way Analysis of Variance for manure plots and a linear-exponential curve fit on the N response plots to determine the shape of the fertiliser response curve and to calculate each site's optimum N fertiliser application and optimum yield.

Table 2. Summary of manures used in the experiment

Code	Supplier	Works	Comments
YW1	Yorkshire Water	Esholt	Dewatered digested cake - some secondary treatment
YW2	Yorkshire Water	Dewsbury	'Standard' dewatered digested cake
YW3	Yorkshire Water	Lundwood	Some treatment/composting
ST1	Severn Trent Water	Mansfield	'Standard' dewatered digested cake
ST2	Severn Trent Water	Derby	'Standard' dewatered digested cake
FYM	ADAS	Gleadthorpe	Old: composted

Manure applications

Six organic sources were used in the experiment. Three were supplied by Yorkshire Water and two were supplied by Severn Trent Water. The sixth was old FYM, sourced from Gleadthorpe. Table 2 provides a brief description.

The application rate of each material was based on a target N loading - either a single dressing (in autumn 1998) of 250, 500 or 750 kg/ha N, or an annual application (in autumn 1998, 1999 and 2000) of 250 kg/ha N. The lowest application rate was based on the guidelines within Defra's Water Code (Anon., 1998). Within this Code, biennial applications of up to 500 kg/ha N are also allowed in some circumstances. The 750 kg/ha N treatment is outside current best practice but was included (a) to test the environmental effects of such a treatment and (b) to increase the likelihood of being able to track the fate of a single application over three years.

Application rate was calculated by taking sub-samples of the manures on delivery and analysing for dry matter and total nitrogen content. These analytical data were then used to calculate the required application rate. The target weight of manure was loaded into a trailer, by driving the trailer over weigh pads, and loading using a tractor fore-end bucket. Spreading over the plot area was achieved by driving the trailer over the length of the plot, unloading progressively by fork and spreading manually across the plot. Samples of manure were taken from each plot as applied, for further chemical analysis.

Fertiliser response plots

These comprised six rates of N, as ammonium nitrate: 0, 40, 80, 120, 180 and 240 kg/ha N. A separate fertiliser response curve was required each year. Because it was inadvisable to use the same fertiliser N response plots each year (because of likely residual effects from the previous fertiliser application, especially at the higher rates) two sets of response plots were included. In the year that a set was not used, these plots received 40 kg/ha N to encourage satisfactory crop growth, but to avoid any significant residual fertiliser effect.

Measurements

Table 3 summarises the measurements that were made throughout the experiment.

Table 3. Summary of measurements made during the solid manure experiments. All manure types were included, though not all application rates, as summarised in the Table.

	Control	Fertiliser response	Manure N rate (kg/ha) 250	500	750	250A*
Manure analysis at spreading:						
Nutrients			✓	✓	✓	✓
Metals			✓		✓	✓
Soil Nmin[1]:						
Spring	✓				✓	✓
Post-harvest	✓				✓	✓
NO_3-N leaching	✓			✓	✓	✓
Harvest data:						
Grain & straw yield	✓	✓	✓	✓	✓	✓
Grain & straw NPK	✓	✓	✓	✓	✓	✓
Grain metals	✓	✓	✓	✓	✓	✓
Topsoil analysis at expt end[1]:						
Nutrients	✓		✓		✓	
Metals	✓		✓		✓	

* Applied annually.
[1] Nmin = soil mineral N (NO_3-N plus NH_4-N), also measured at the start of the experiment on a block basis.

Measurements were made across all manure types. However, resources did not allow all measurements to be carried out across all rates. Because the intention was to follow the fate of applied N over three years, measurements that would contribute to measuring the N balance were always made on the 750N rate. This large application rate had been included specifically to follow the N pathways. However, subsidiary information on the fate of N was obtained from all rates. Similarly, all rates gave valuable information on Fertiliser Replacement Value and crop N utilisation. The methods are described fully in Section 4.2.3.

4.2.2 Liquid manures

Whereas the solid manure experiments focused on the longer-term release of N from the organic fraction, the aim of the liquid manure experiments was to study the much larger ammonium-N (NH_4-N) fraction. Therefore, a series of annual experiments was used, investigating the effects of top-dressing cereal crops. There were two sites in each year.

Sites

Two farms hosted the experiments, with the experiment moved to a different field on each farm, each year (Table 4).

Table 4. Site details for the liquid manure experimental sites.

Address:	Old Hatton Farm, Pendeford, Staffs.	ADAS, Bridgets Research Centre, Winchester, Hants.
Abbreviation:	Ht	Br
Grid reference:	SJ 883 055	SU 526 338
Altitude:	110m	100m
Soil type:	1999: Salwick; SL over SL-SCL 2000: Salwick; SL over SCL with mottling 2001: Salwick; SL over SL-SCL	1999: Panholes; calcareous ZCL over chalk at 30-40cm 2000: Andover; calcareous ZCL over chalk at 30cm 2001: Andover; calcareous ZCL over chalk at 30cm
Annual average rainfall:	773 mm	628 mm

The site supplied by Severn Trent Water (Hattons Farm: Ht) was the 'core' site and so included detailed measurements of ammonia loss and nitrate leaching. The second site, at ADAS Bridgets (Br), included assessments only of crop yield and fertiliser N equivalent values of the manure applications. The sandy soil at Ht provided a useful test of leaching risk.

Experiment design and statistical analysis

Each experimental site included the following treatments:

- Control, receiving no manure;
- Four manures applied at four timings;
- Fertiliser response plots.

There were three replicates of each treatment, giving a total of 69 plots:

	No. of treatments	No. of plots
Un-manured control	1	3
4 manures x 4 application times	16	48
Fertiliser response plots	6	18
Total	23	69

Each plot was 3 m x 12 m.

Statistical analysis was based on two-way Analysis of Variance for manure plots and a linear exponential curve fit on the N response plots to determine the shape of the fertiliser response curve and to calculate each site's optimum N fertiliser application and optimum yield.

Manure applications

Four organic manures were used in the experiment:

1. Pig slurry
2. Cattle slurry
3. Liquid digested sewage sludge (supplied by Yorkshire Water)
4. Liquid digested sewage sludge (supplied by Severn Trent Water)

The application rate of each material was based on a target N loading of 120-150 kg/ha total N. Application rates were based on a preliminary analysis of the material prior to spreading. There were four separate application timings:

5. October (Band spread, 30 cm spacing, after drilling)
6. GS 24/26 (Band spread, 30 cm spacing)
7. GS 30 (Band spread, 30 cm spacing)
8. GS 39 (Band spread, 30 cm spacing)

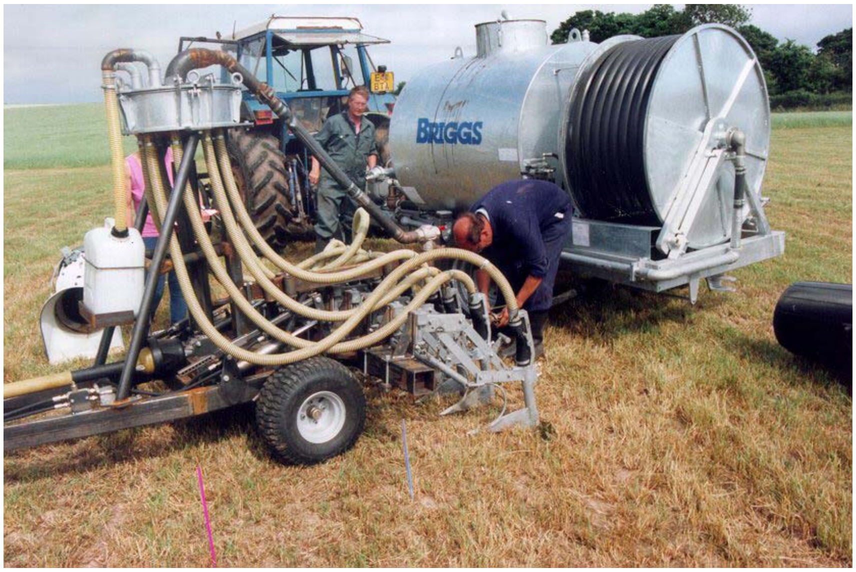


Figure 2. Plot applicator used for applying liquid manures.

The same manures were used for all applications at both sites each year, by transporting a sufficient quantity to each site and storing it in covered tanks. The liquids were thoroughly stirred before application to ensure a homogenous material on each occasion. The liquids were applied with the ADAS precision plot applicator (Fig. 2), which placed the manures on the soil surface in bands, about 30 cm apart. Application rate was based on an analysis of the manure pre-spreading (for total N). Further sub-samples were taken at spreading for a full analysis.

Fertiliser response plots

These comprised six application rates of prilled ammonium nitrate: 0, 40, 80, 120, 160 and 240 kg/ha N. Because the experiment moved to a new field each year, there was no need for fertiliser 'rest' plots in the way that were necessary to overcome the residual effect of previous N fertiliser applications in the solid manure experiment.

Measurements

Table 5 summarises the measurements made throughout the experiment. All manure types were included, though not all application timing treatments, as summarised in the Table.

Table 5. Summary of measurements made during the liquid manure experiments.

	Control	Fertiliser response	Manure type			
			Pig Sl.	Cattle Sl.	LDS 1	LDS 2
Manure analysis at spreading:						
Nutrients			✓	✓	✓	✓
Metals			✓	✓	✓	✓
Soil Nmin[1]:						
Spring						
Post-harvest	✓		✓	✓	✓	✓
NO_3-N leaching:						
Autumn application	✓		✓	✓	✓	✓
NH_3-N volatilisation:						
GS 24/26 application			✓	✓	✓	✓
GS 30 application			✓	✓	✓	✓
Harvest data:						
Grain & straw yield	✓	✓	✓	✓	✓	✓
Grain & straw NPK	✓	✓	✓	✓	✓	✓
Grain metals	✓	✓	✓	✓	✓	✓

[1] Nmin = soil mineral N (NO_3-N plus NH_4-N), also measured at the start of the experiment on a block basis.

4.2.3 Methods

Manure analysis

Each year, manure analysis pre-spreading was carried out (DM and N content), to calculate application rate (as described above) and followed by sampling and analysis of the material, as-spread (DM, total N, NH_4-N, NO_3-N, total C, P, K, Mg and pH). Analysis for heavy metals (zinc, copper, nickel, cadmium, lead, chromium) and P fractionation were also undertaken. There were 3 sub-samples per manure type taken, pre-spreading and 3 (liquids) or 4 (solids) sub-samples per manure type taken for the full analysis, at the spreading.

Soil mineral N (Nmin)

Depth sampling of soil for Nmin (NH_4-N plus NO_3-N) was done to 90 cm (to 60 cm on shallower soils) using a “HydroCare” ATV-mounted automatic soil sampler (Levington Agriculture, Suffolk, Ipswich). The depths were sampled in 30 cm increments, bulking 6 cores per sample. Soils were frozen for storage and transport to the laboratory. Before analysis, they were thawed overnight at room temperature.

Nitrate leaching

Porous ceramic cups (4 per plot) were installed according to the method of Webster *et al*. (1993) to a depth of 1 m (Gt; Ht) or 0.6 m (Em), due to a stony subsoil at this site. The porous cups were sampled at fortnightly intervals through the autumn and winter drainage season. Water samples were analysed for NO_3-N. Start and finish of drainage was calculated by the ADAS "Irriguide" package (Bailey & Spackman, 1996). Drainage start was confirmed by soil sampling to assess gravimetric moisture content. From the modelled drainage and the measured NO_3-N concentrations, the total NO_3-N loss during the drainage season was calculated according to the method of Lord & Shepherd (1993).

Yield measurement and grain/straw analysis

All plots were harvested individually by small plot combine and grain samples were taken for dry matter, total N and total P analysis. Dry matter harvest index samples were taken just before harvest and analysed for total P and total N. This enabled the partitioning of N and P between grain and straw to be calculated, thus providing a measure of total above ground N and P uptake at harvest (to assist nutrient balance calculations). Selected treatments also had grain analysed for zinc, nickel, copper, chromium, cadmium and lead.

Topsoil samples

Topsoil (0-20 cm) samples were collected for nutrient and metal analysis by bulking 20 cores per sample, taken using a cheese-core auger. Soils were analysed for heavy metals, pH, P, K, Mg, total N and total C.

Ammonia emissions (liquid experiment only)

Additionally at the Ht site, measurements of ammonia loss were made from the manure applications at GS24 and GS30 using the dynamic chambers method (Svensson, 1994). Emissions of ammonia were measured on control and treated plots, commencing immediately after treatment applications. Measurements continued for a three-day period, consisting of three 1-hour periods (approx.) on the first day, two 2-hour periods (approx.) on the second day, and one 4-hour period on the third day.

Estimation of fertiliser replacement value and percentage N recovery

These are key calculated values in the project and therefore warrant considerable detail of their background and methodology. They are therefore described below.

4.2.4 Estimation of fertiliser replacement value and apparent N recovery

In manure experiments investigating N fertiliser value, the fertiliser equivalence of the manure is commonly expressed as 'Fertiliser Replacement Value' (FRV). Another commonly used term, meaning the same, is 'N efficiency' of the manure.

Fertiliser Replacement Value or N efficiency can be defined as the proportion of the manure's total N content that is equivalent to an application of inorganic N fertiliser (usually ammonium nitrate) applied according to best practice in the spring. So, if a manure has a FRV of 10%, this means that out of an application of, say, 250 kg/ha total N, it will supply to the crop an amount of N equivalent to 25 kg/ha N as ammonium nitrate fertiliser.

Ammonium nitrate is taken as the standard for calculating FRV. Then, the FRV can be subtracted directly from the fertiliser recommendation that would apply in the absence of manure to calculate the required application of bagged fertiliser, e.g.:

fertiliser recommendation for a crop of winter wheat:	180 kg/ha N
fertiliser replacement value of 30 m^3/ha pig slurry:	100 kg/ha N
fertiliser requirement from the bag:	**80 kg/ha N**

The FRV will depend on many factors, including the amount of N in the manure and the likely losses after application. The aim of this project was to get a better estimate of the FRV for a range of manures and sewage sludges.

Calculation of FRV - yield data

This requires the inclusion of a nitrogen response curve. For example, Figure 3a shows the relationship between crop yield and applied N fertiliser (i.e. applied according to best practice in the spring).

A curve fitting procedure is used to describe the yield response data. Most commonly (George , 1984), a linear plus exponential relationship has been used, of the form:

$$\text{yield} = A + B\, r^N + C\, N$$

where A, B, C and r are constants and N = N fertiliser rate. The value of r is generally close to 0.99, but is allowed to vary during the optimisation process. By measuring the yield from a treatment which has received only manure N which can be compared with a yield response curve based on fertiliser N, the amount of ammonium nitrate fertiliser needed to achieve the same yield can be established (Fig.

3b). Dividing this amount by the total N in the manure gives the FRV, which is normally presented as a percentage of the total manure N applied (Fig. 3c).

This approach includes an important assumption: that any yield benefit from the manure application is derived only from the N contained within that manure (i.e. not from other major or minor nutrients, nor from any added benefit of added organic matter). While experience has shown that the approach works in most cases, there are occasions when the yield from the manure treatment falls above the fertiliser response curve. Thus, some added benefit from the manure application must be invoked. This risk can be minimised by applying PK fertilisers to the N response curve plots if there are low background levels of soil nutrients.

Calculation of FRV - other response data

As well as calculating the FRV from the N response curve, a similar calculation can be made using the relationship between applied fertiliser and the grain or (grain plus straw) N uptake by the cereal crop. Unlike yield, the relationship between applied N fertiliser and grain N uptake is linear either over the entire experimental range (as in the case of Fig. 4a), or sometimes there is a breakpoint where the rate of N uptake decreases. If this occurs, it is usually close to the optimum N fertiliser rate.

Using this linear, or a two straight-line relationship, the same principles then apply to the calculation of FRV (Fig. 4a-4c).

Estimation of apparent N recovery

It is also common to calculate the 'Apparent N recovery' of the manure N in the grain. This again is expressed as a percentage of the total N applied in manure, and is calculated thus:

X = grain N uptake by manure treatment, receiving Y kg/ha total N as manure;
Z = grain N uptake by control treatment receiving no manure or fertiliser N (supply only from soil N supply).

Apparent N recovery % = (X-Z)/Y x 100

This assumes that the N supply from the manure treatment would be the same as for the control. i.e. the N uptake from the manure is purely additive.

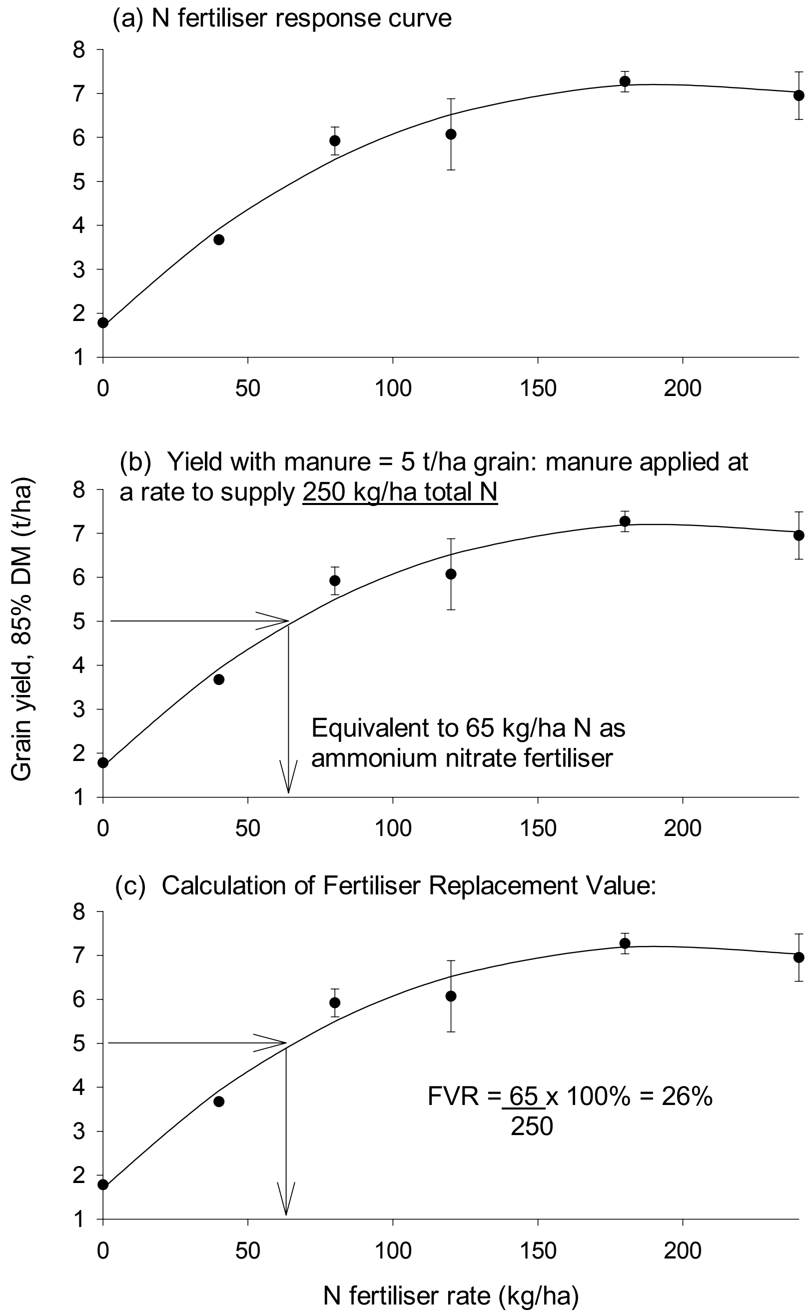


Figure 3. Calculation of the Fertiliser Replacement Value of manure N, based on a response curve of grain yield versus ammonium nitrate fertiliser rate applied. Example data.

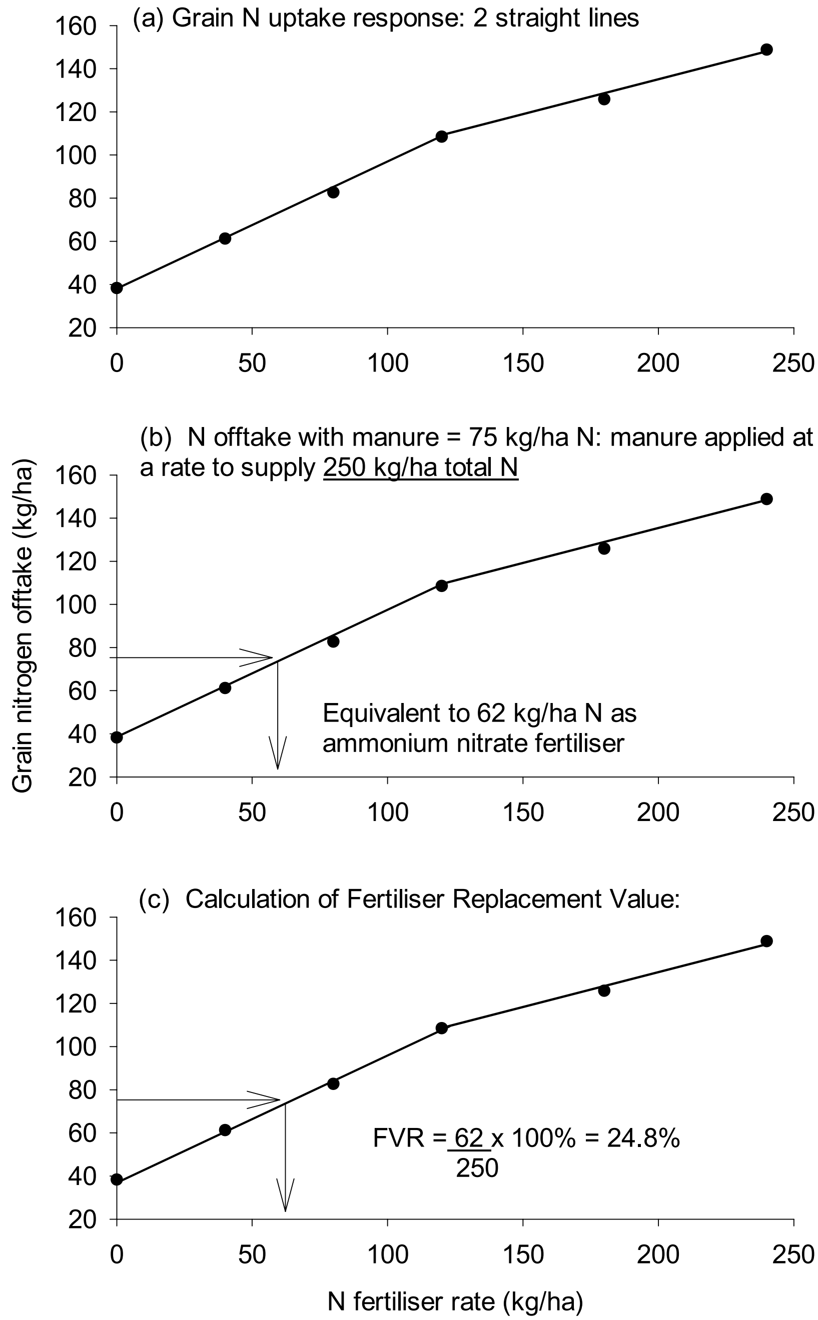


Figure 4. Calculation of the Fertiliser Replacement Value of manure N, based on the response of grain nitrogen off-take versus ammonium nitrate fertiliser rate applied. Example data.

4.2.5 Site husbandry

Solid manure experiments

1998/99

At Gleadthorpe, winter wheat (cv. Rialto) was drilled following the application of manure/sludges. In mid-November, the manure/sludges were applied to plots as per the protocol. The field was then plough/pressed and drilled with winter wheat on 20 November 1998. Differential nitrogen was hand applied to the N response curve treatments in mid-March and mid-April. The crop was unirrigated throughout. Plots were harvested on 6 August 1999.

At Emley, following the application of the manures /sludges between 21 and 23 October 1998, winter wheat (cv. Riband) was drilled on 7 November. In late October, the manures/sludges were applied to plots as per the protocol. The field was then ploughed and power harrowed and drilled with winter wheat on 7 November 1998. The crop emerged thinly and so a decision was made to apply 50 kg/ha fertiliser N overall in early March. All N response treatments received further nitrogen in March and April 1999. Plots were harvested on 8/9 September 1999. The crop was unirrigated.

1999/00

At Gleadthorpe, the sludges were applied to plots as per the protocol (250 kg/ha N annually) on 1 November 1999. The field was then plough/pressed on 5 November and drilled with winter wheat (cv. Rialto) on 9 November. Differential N was hand applied to the N response curve treatments in late March and mid-April 2000. The crop was unirrigated and the plots were harvested on 24 August 2000.

At Emley, the sludges were applied to the plots as per the protocol (250 kg/ha N annually) on 21 September 1999. The field was then plough/pressed and drilled with winter wheat (cv. Riband) on 7 October. Differential nitrogen was hand applied to the N response plots in mid-March and mid-April 2000. The field was unirrigated and the plots were harvested on 13 September. This was late due to rain around the time the crop became ripe enough to harvest.

2000/01

At Gleadthorpe, the sludges were applied to plots as per the protocol (250 kg/ha N annually) on 14 and 22 November 2000. The field was plough/pressed on 15 December and drilled with spring barley (cv. Optic) on 16 December. Differential N was hand applied to the N response curve treatments in late March and late April 2001. The field was unirrigated and the plots were harvested on 1 August.

At Emley, the sludges were applied to the plots as per the protocol (250 kg/ha N annually) on 13 October 2000. The field was then plough/pressed and drilled with winter wheat (cv. Consort) on 26 October. Differential nitrogen was hand applied to the N response plots in one application rather than a split, on 11 April 2001. This was necessary because of limited access to the site due to the foot and mouth restrictions. The field was unirrigated and the plots were harvested on 5 September.

Liquid manure experiments

<u>1998/99</u>

At Ht, winter wheat (cv. Hereward), was drilled in early October, with the liquid sludges and slurries applied as a top-dressing in mid-November. Further liquid manure top-dressings were applied in February (GS24), April (GS30) and in early June (GS39). The fertiliser N response plots received prilled ammonium nitrate fertiliser in two applications, with an early 40 kg/ha in March and the balance (to supply a total of 0, 40, 80, 120, 160 and 240 kg/ha N) in April. Crop husbandry operations, including the need for pesticide and growth regulator sprays were carried out, as appropriate, by farm staff, in line with the requirements for the rest of the field. The plots were harvested in August.

At Br, winter wheat (cv. Reaper), was drilled in early November, following the initial liquid sludge and slurry applications on the stubble, in late October. Further liquid manure top-dressings were applied in March (GS30), April (GS31) and in early June (GS43). The March application was inevitably delayed because of extreme wetness and poor soil conditions (an earlier application, March 1, abandoned). As in other years, at both sites, other crop husbandry operations were carried out by farm staff, in common with the requirements of the rest of the field. The plots were harvested 23 August.

<u>1999/00</u>

At Ht, winter wheat was drilled in 15 October, following the initial liquid sludge and slurry applications on the stubble, on 21 September. Further liquid manure top-dressings were applied on 22 February (GS24), 17 March (GS30) and on 24 May (GS39). Wet weather and poor soil conditions were a problem throughout the winter and early spring, resulting in significant damage to plots and run-off following the application of slurries and sludges. The fertiliser N response plots received prilled ammonium nitrate fertiliser in two applications, with an early 40 kg/ha in March and the balance (to supply a total of 0, 40, 80, 120, 160 and 240 kg/ha N) in April. The plots were harvested in August.

At Br, winter wheat (cv. Consort) was drilled 16 September, following ploughing in of the initial liquid sludge and slurry applications on the stubble, the previous day. Further liquid manure top-dressings were applied on 22 February (GS24), 30 March (GS30) and on 22 May (GS39). In contrast to the previous year, spring treatments were applied under good conditions. The plots were harvested 21 August.

<u>2000/01</u>

At Ht, in common with many farms in the area severe, wet weather during the autumn delayed field work and drilling on the intended site. It was therefore necessary to change the cropping plan from an autumn to a spring-sown cereal, which was drilled in February. The adverse weather, therefore, resulted in the loss of not only the autumn slurry and sludge treatments, but also the opportunity to study nitrate leaching losses from these treatments, during this year. The remaining liquid manure treatments were applied as bandspread top-dressings on 27 March (GS24), 31 April (GS30) and on 22 May (GS39). The fertiliser N response plots received prilled ammonium nitrate fertiliser in two applications, with an early 40 kg/ha in March and the balance (to supply a total of 0, 40, 80, 120, 160 and 240 kg/ha N) in April. The plots were harvested in August.

At Br, winter wheat (cv. Consort), was drilled 9 November, following application of the initial liquid sludge and slurry applications, 27 October. As in previous years, the initial manure treatments were applied using the plot applicator, using the trailing hose attachments. However, the Foot and Mouth Disease crisis which started in February 2001 meant that this equipment could not be moved from its Midlands base and subsequent liquid manure top-dressings had to be applied manually using calibrated buckets: 30 March (GS24), 5 May (GS31) and on 23 May (GS43). The early fertiliser N (40kg/ha N) was applied to the N response plots, March 30, with the main application, May 5th. In contrast to the previous year, spring treatments were applied under good conditions. The plots were harvested 21 August.

4.3. Laboratory Studies

4.3.1 Introduction

The organic fraction of FYM and sewage sludge cakes makes an important contribution to the N fertiliser value of these materials. However, the rate of breakdown of this organic fraction (and hence its fertiliser value) is through microbial action. Consequently, factors that affect this breakdown include:

- The composition of the organic fraction: its carbon: nitrogen ratio and the composition of the complex organic compounds: i.e. how easily degradable they are;
- The soil environment: temperature, moisture content and aeration.

Given these influences, it is very difficult to predict N supply precisely, especially given the possible variations between batches of manure. However, this project tests the hypothesis that some further improvement can be made. To increase understanding, laboratory incubations are one possible tool. By adding the materials to soil and incubating at controlled moisture and temperature conditions, this allows us to learn a considerable amount about the breakdown of the organic components, especially when allied to field experiments as described earlier.

Incubation studies were therefore included to provide further understanding of the breakdown of the organic fraction of the sewage sludge materials and the FYM used in the solid manure experiments.

4.3.2 Objectives

- To undertake laboratory-based incubations to gauge the N release from a range of manures and sludges as used in the field experiment phase of this project.
- To correlate N release characteristics with (a) field data on cereal N uptake and crop N response and (b) NIRS analysis of the samples.

4.3.3 Methods

The procedures were undertaken on two separate occasions: 1999 and 2000.

Sludge and manures

The same six organic sources were used in the incubations as in the field experiments. Three were supplied by Yorkshire Water and two were supplied by Severn Trent Water. The sixth was old FYM, sourced from Gleadthorpe. The manures as spread on the Gleadthorpe site were used for the incubation experiments. Sub-samples were collected at the time of spreading, and had been submitted to the laboratory for a full nutrient analysis. Small sub-samples were retained and stored in the cold store, and these were used for this experiment.

To enable even mixing of the manure samples with the soil for the incubation studies, the manure samples were dried and ground. This was achieved by breaking about 800 g of 'fresh' manure into small nuggets, and drying overnight at *c.* 30 ^{o}C. A 100 g sub-sample was then finely ground with a mortar and pestle for use in the incubations. The remainder was submitted to the laboratory for dry matter, carbon, ammonium N and total N determination. The oven drying had the benefit of driving off most of the ammonium so that the incubations were able to assess the mineralisability of the organic fraction.

Soil preparation

Loamy sand soil from ADAS Gleadthorpe was used to mix with the manures. This was thought the ideal medium, allowing good aeration and avoiding possible denitrification losses. It was necessary to handle the soil in such a manner that would avoid a flush of mineralisation activity at the start of the experiment. This was achieved by collecting about 15 kg of topsoil from a site on which we expected low mineral N residues. This was stored in a cold store at 4 ^{o}C while the gravimetric moisture content was determined on 3 sub-samples. This allowed calculation of the amount of water required bringing the soil to 60% of Water Holding Capacity (previously measured for this soil-type). The required amount of water was added to 14 kg soil by spreading the soil on a polythene sheet, applying the water and thoroughly mixing with a spade. The soil was returned to the coldstore until required (approximately 3 days).

Laboratory incubations

The incubations were undertaken by mixing the dried, ground manure with moist soil and then incubating the soil/manure mixture either aerobically or anaerobically. A control treatment (i.e. no manure addition) was also included, providing 7 treatments in total.

Aerobic incubations

100 g dried, ground manure was thoroughly mixed with 1.9 kg of moist soil. Four sub-samples of the mix ('time zero') were taken for Nmin analysis, and a further three sub-samples were taken for gravimetric moisture content determination.

Then, 50 g sub-samples were weighed into glass incubation vessels. Identifiers for manure type and weight of soil were written onto the vessel. The vessel top was covered with parafilm with holes pricked in it (to minimise moisture loss, but to enable air exchange). Sufficient jars were filled with each manure type to enable 4 to be removed and destructively sampled for Nmin at 1, 2, 3, 5, 8 and 16 weeks. The soils were incubated at 20 °C and their weights checked at weekly intervals for moisture loss: corrections were made by adding distilled water as necessary, though losses were minimal.

Anaerobic incubations

The remaining soil/manure mixes were used for the anaerobic incubations. Four replicates of each (including the control soil) were set up. Following the standard ADAS procedure, 32 g was weighed in to a glass jar, flooded with 80 cm^3 deionised water, sealed and placed in an incubator for 1 week at 40 °C.

Extractions for Nmin

For the aerobic incubations, all of the soil was scraped in to the extraction vessel and the residual soil washed with extractant (2M KCl). An extraction ratio of 2:1 extractant:soil was used, shaking for 2 hours and filtering through a number 42 Whatman filter paper. Extracts were stored fresh and submitted to the laboratory for Nmin measurement.

For the anaerobic incubations, the soil/water mix was poured into the extraction vessel, 80 cm^3 of 4M KCl added, shaken for 2 hours and filtered and analysed as above.

Using the gravimetric moisture contents determined at the start of the experiment, results were expressed as mg N per kg dry soil.

NIRS

NIRS is near infrared spectroscopy. The instrument detects the spectrum of the sample in the near infrared. This part of the spectrum contains a lot of information about C-H, N-H etc. bonds. Sub-samples of the dried, ground and fresh manures were submitted to the laboratory for analysis by Near Infra-red methods. Each sample was placed in a NIRS cell (fresh samples wrapped in cling film first). They were then scanned on the NIRS (NIRSystems model 6500) in reflectance mode over the range 400-2500 nm.

4.4. Demonstration Plots

This was where application techniques and agronomic effects were demonstrated on a semi-field scale. Aspects of the more successful strategies identified in the liquid and solid manure experiments were to be selected and applied across large field areas, using commercially available equipment. These large, unreplicated plots were not intended to form part of the scientific experiments, but were designed to demonstrate an integrated approach to planning manure N use, in combination with fertiliser N. Yield mapping by both a GPS equipped combine harvester, or a grid sampling of the plots using the small plot combine, was attempted to aid critical assessments of the results from these sites.

Field sites were selected, not only on the basis of soil fertility and uniformity, but also with some thought for site aspect and suitability for visual inspection by visitors during the proposed open days to be held in each of the second and third years of the project.

Sites were successfully completed in 2000, with over 100 visitors attending each site (Fig. 5):

- Old Hatton Farm, Staffs;
- Bedale Castle, North Yorks.

Old Hatton Farm | Bedale Castle

Figure 5. Demonstration sites 2001.

Figure 6. Trailing hose applicator (left) and Tramspread (right) application systems used at the demonstration sites, 2000.

The Foot and Mouth Disease outbreak of 2001 meant that proposed sites for that year had to be aborted. As a replacement event, demonstration plots were set up at the Cereals 2002 event in Sleaford (Fig. 1 for location). More details are provided later.

The plots on the two demonstration sites in 2000 generally comprised an area of 24 m x 100 m (c. 0.24 ha), the exact dimensions depending upon tramline width, as well as soil and field considerations. Slurry, FYM, solid and liquid sludge applications were undertaken using farm or contractor equipment. The techniques included rear-discharge solids spreaders for FYM and sludge cakes (in autumn); surface broadcast via boom and splashplate (Fig. 6), or trailing hose applicator (Fig. 6), for the slurries and liquid sludges (in spring).

Integration of the N supplied by the manures and supplementary fertiliser dressings on these plots, was based on predictions derived from the ADAS MANNER decision support system (Chambers *et al.*, 1999). At least one plot provided a direct comparison with conventional fertiliser N policy, typical of host farm practice. As well as harvest yield and a simple economic assessment of the results based on inputs and yields, the plots were occasionally inspected for visual growth patterns, any marked wheeling effects or crop scorch which may have been associated with the manure applications. It was the intention of the programme to include, also, an aerial reconnaissance survey, at an appropriate stage during the summer, to aid critical assessment of the field operations. However, an unusually wet spring/summer meant that flying conditions were never good enough to obtain good photographs of the site.

It was anticipated that this pragmatic and simple 'commercial' approach would provide a good 'platform' to demonstrate the economic and environmentally sustainable use of organic manures within practical arable farming. Further details are reported under 'Results'.

5. RESULTS

5.1. Small Plot Experiments

5.1.1 Solid manures

Soil analysis at the start of the experiment

Starting soil nutrient and metal concentrations were typical for the respective soil-types at the Gt and Em sites (Table 6). Soil Nmin was measured on each block in the autumn before the manures had been applied. Levels were also typical of soil-type and rotation (Table 7). At Gleadthorpe, 88 kg/ha N was measured to 90 cm following a cereal crop. The Nmin was evenly distributed down the soil profile. At Emley, the previous crop had been oilseed rape. Consequently, there were moderately large soil Nmin levels at the start of the experiment (mean 126 kg/ha N), and also with some variation between blocks. Most was present in the topsoil at the time of sampling.

Table 6. Chemical analysis of the topsoil at the start of the experiment, November 1998.

(a) nutrients (mean of 39 plot samples)

Measurement	Unit	Gleadthorpe				Emley			
		mean	min	max	CV	mean	min	max	CV
pH		6.7	6.5	7.1	2%	7.0	6.7	7.2	2%
Extractable P	mg/l	38	26	53	15%	29	20	36	14%
Extractable K	mg/l	98	79	127	12%	174	110	212	12%
Extractable Mg	mg/l	97	74	118	10%	286	241	351	7%
Total N	%	0.10	0.08	0.12	9%	0.25	0.21	0.29	7%
Organic matter	%	2.8	1.6	4.05	32%	4.7	2.4	5.4	19%

(b) total metals (mean of 9 plot samples)

Metal	Unit	Gleadthorpe				Emley			
		mean	min	max	CV	mean	min	max	CV
Pb	mg/kg	14.1	8.5	18.6	25%	48.8	42.1	57.2	11%
Ni	mg/kg	4.9	3.8	5.7	13%	17.5	16.3	20.7	9%
Zn	mg/kg	22.4	18.9	25.6	11%	62.3	83.7	103.0	9%
Cd	mg/kg	0.2	0.1	0.2	21%	0.3	0.2	0.3	21%
Cr	mg/kg	6.8	5.6	7.8	11%	24.0	22.0	26.3	7%
Cu	mg/kg	4.0	3.2	4.7	11%	27.0	22.3	39.3	23%

Table 7. Nmin (kg/ha) at experiment start by depth by block (measured November 1998)

Block	0-30 cm	30-60 cm	60-90 cm	0-90 cm
Gleadthorpe				
I	26	42	22	90
II	26	22	27	75
III	42	28	28	98
Mean	31	31	26	88
Emley				
I	63	23	11	96
II	126	23	13	162
III	96	15	9	120
Mean	95	20	11	126

Manure nutrient characteristics and nutrient loading

Manure applications at the start of the experiment were especially critical, since the aim was to monitor the effects of these applications over the following three years.

Table 8. Manure nutrient analysis, applied autumn 1998, expressed on a fresh weight basis.

Manure type	DM %	N kg/t	NH_4-N kg/t	NO_3-N kg/t	P_2O_5 kg/t	K_2O kg/t	MgO kg/t
(a) Gleadthorpe							
YW1	26	6.2	0.7	0.00	6.1	1.2	1.0
YW2	25	9.3	1.8	0.05	7.7	0.5	1.5
YW3	37	8.6	0.4	1.15	10.3	1.1	2.3
ST1	27	9.7	1.1	0.00	10.3	0.4	2.1
ST2	31	9.5	1.8	0.03	14.8	0.6	2.5
FYM	43	6.3	0.1	0.69	3.5	10.7	2.8
(b) Emley							
YW1	26	8.2	0.3	0.00	9.0	0.6	0.9
YW2	26	9.1	1.4	0.01	8.0	0.7	1.9
YW3	42	13.6	2.8	0.46	13.3	1.4	2.9
ST1	23	9.7	1.7	0.01	9.5	0.4	1.9
ST2	31	9.6	1.8	0.02	16.1	0.7	2.6
FYM	37	5.3	0.1	0.48	3.2	8.6	2.6

Nutrient content varied between the different materials in the first year. This trend was noted at both sites (Table 8). Dry matter was generally about 25%, with three exceptions: the composted YW sludge (YW3), the old FYM, which was stored under cover, and ST2. The FYM had clearly undergone some N transformations during storage, as indicated by the relatively high nitrate-N content. Elevated nitrate levels were also measured in the composted YW3 sludge. All other sludges generally contained minimal amounts of nitrate in the first year.

Target applications of manure were based on a total N application of 250, 500 and 750 kg/ha. On average, these targets were generally achieved at both sites (Table 9). The aim for Treatment 4 was that annual applications equivalent to 250 kg/ha N should be made. Details of the first application (autumn 1998) are shown above. Table 10 shows the N loadings for each of the annual treatments.

Table 9. Nitrogen loadings (kg/ha) achieved for each treatment, autumn 1998.

Manure type	Target 250 kg/ha N			Target 500 kg/ha N			Target 750 kg/ha N		
	Total N	NH_4-N	NO_3-N	Total N	NH_4-N	NO_3-N	Total N	NH_4-N	NO_3-N
(a) Gleadthorpe									
YW1	239	28	0	480	57	0	722	86	0
YW2	264	50	2	520	98	3	780	147	5
YW3	225	11	30	443	21	59	662	32	89
ST1	228	26	0	467	54	0	703	81	0
ST2	255	48	1	508	95	1	756	142	2
FYM	268	4	29	533	7	58	806	11	88
(b) Emley									
YW1	226	7	0	451	14	0	687	21	0
YW2	252	38	0	505	75	0	762	114	1
YW3	264	55	9	521	109	17	791	165	27
ST1	234	41	0	467	82	0	710	124	0
ST2	258	48	0	514	97	1	769	145	1
FYM	237	5	22	448	10	41	663	15	60

Table 10. N loadings achieved each year for the 250 kg/ha N annual application.

Manure type	Year 1			Year 2			Year 3			Total		
	TotN	NH_4-N	NO_3-N	TotN	NH_4-N	NO_3-N	TotN	NH_4-N	NO_3-N	TotN	NH_4-N	NO_3-N
(a) Gleadthorpe												
YW1	245	29	0	216	2	21	196	2	7	657	33	7
YW2	263	50	2	254	32	17	187	35	1	704	117	3
YW3	223	11	30	258	2	42	215	0	10	696	13	40
ST1	237	27	0	252	54	0	369	87	0	858	168	0
ST2	258	48	1	284	60	0	281	57	0	823	165	1
FYM	267	4	29	211	2	36	305	1	2	783	7	31
(b) Emley												
YW1	230	7	0	367	2	16	247	41	0.41	844	50	16
YW2	255	38	0	202	7	0	208	26	0.29	665	71	1
YW3	267	56	9	373	3	20	170	13	1.63	810	72	31
ST1	234	41	0	228	77	0	278	60	0.22	740	178	0
ST2	254	48	0	305	60	0	230	36	0.41	789	144	1
FYM	221	5	20	181	3	21	307	20	5.75	709	28	47

Manure metal content

Metal concentrations in the manures were not especially high in any of the samples throughout the experiment. Table 11 provides data for the first applications in autumn 1998, Though data for other applications are not shown, all metal loadings were well within the permissible maximum loadings.

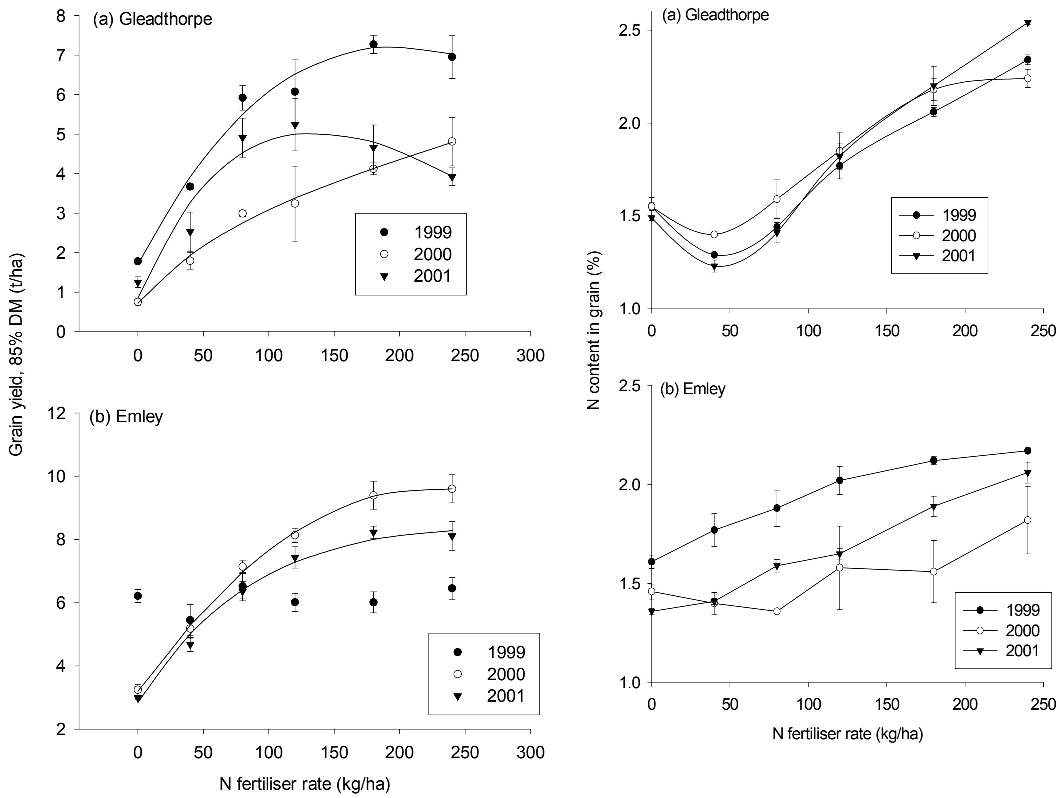
Table 11. Manure metal analysis, applied autumn 1998, expressed on a dry matter basis

Manure type	pH	DM g/kg	Pb mg/kg	Ni mg/kg	Zn mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg
(a) Gleadthorpe								
YW1	8.1	265	113	17	305	0.9	45	114
YW2	8.0	246	142	35	967	1.5	310	272
YW3	5.3	372	119	35	536	1.8	50	236
ST1	7.3	267	158	56	566	1.7	69	356
ST2	7.8	310	590	140	2098	4.9	167	371
FYM	8.3	429	14	5	83	0.4	10	26
(b) Emley								
YW1	8.1	258	139	20	325	1.0	60	144
YW2	8.0	262	183	34	958	1.6	245	220
YW3	5.3	415	155	41	659	2.2	72	268
ST1	7.3	234	117	57	585	1.7	65	370
ST2	7.8	313	572	131	2118	5.0	176	388
FYM	8.3	367	14	7	99	0.2	8	29

Grain yield, N off-take and fertiliser replacement value

Fertiliser response

Table 12 shows the responses in yield, grain N off-take and grain N concentration from the fertiliser response plots each year (i.e. no sludges applied). Figure 7 shows the graphical representation of these data with fitted linear plus exponential curves (yield), two straight lines (grain N off-take) or sigmoidal curves (grain N concentration). In four of the six site years, grain N response followed the typical pattern of a steady increase to the optimum, followed by a plateau and/or decline above the optimum. Optimum N fertiliser rate and associated yield for each experiment were calculated by the method of George (1984) where satisfactory curve-fits were obtained (Table 13). The two exceptions were year 1 at Emley where there was no yield response to added fertiliser N. At Gleadthorpe, for the 2000 harvest, the N response curve did not reach a plateau. However, the data could still be used to calculate fertiliser replacement values in this second year: this was not possible at Emley due to the lack of response to fertiliser.



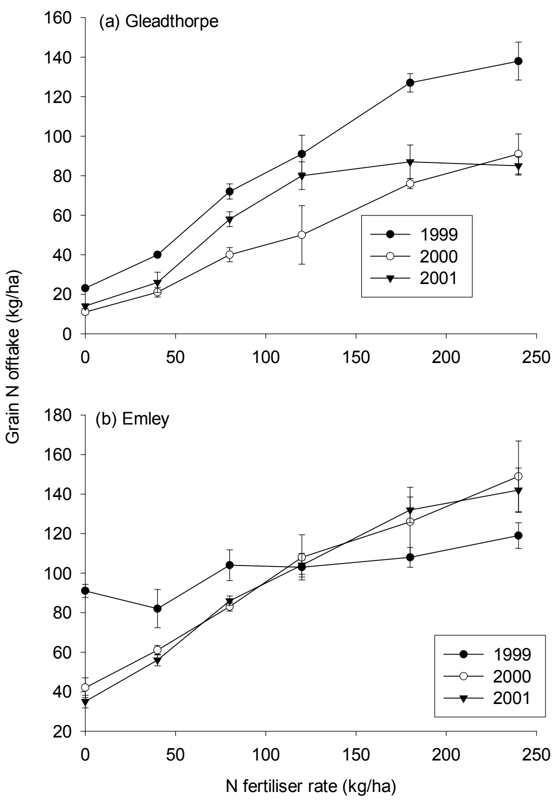


Figure 7. Fertiliser N effects on grain yield response (top left), grain N concentration (top right) and grain N off-take (bottom left) at the solid manure experiment sites. With standard errors.

Table 12. Yield data from N fertiliser response treatments.

(a) Gleadthorpe

	0	40	80	123	180	240	SED* min	SED* mxmn	*P*
Grain yield (t/ha, 85% DM)									
1999	1.78	3.67	5.92	6.07	7.27	6.95	0.507	0.439	0.001
2000	0.75	1.79	2.99	3.24	4.12	4.81	0.641	0.555	<0.001
2001	1.25	2.53	4.91	5.24	4.66	3.92	0.583	0.505	<0.001
Grain N (%)									
1999	1.58	1.29	1.44	1.77	2.06	2.34	0.049	0.043	0.001
2000	1.50	1.40	1.59	1.85	2.18	2.24	0.112	0.097	<0.001
2001	1.49	1.23	1.41	1.82	2.20	2.54	0.064	0.055	<0.001
Grain N off-take (kg/ha)									
1999	24	40	73	91	127	138	7.5	6.5	0.001
2000	10	21	40	50	76	91	10.2	8.9	<0.001
2001	16	26	58	80	87	85	6.9	6.0	<0.001

(b) Emley

	0	40	80	123	180	240	SED* min	SED* mxmn	*P*
Grain yield (t/ha, 85% DM)									
1999	6.21	5.45	6.52	6.01	6.01	6.45	0.507	0.439	0.369
2000	3.23	5.18	7.14	8.13	9.39	9.60	0.450	0.389	<0.001
2001	3.00	4.68	6.36	7.43	8.23	8.11	0.356	0.308	<0.001
Grain N (%)									
1999	1.63	1.77	1.88	2.02	2.12	2.17	0.080	0.069	<0.001
2000	1.39	1.40	1.36	1.58	1.56	1.82	0.181	0.156	0.142
2001	1.36	1.41	1.59	1.65	1.89	2.06	0.050	0.043	<0.001
Grain N off-take (kg/ha)									
1999	61	82	104	103	108	119	8.4	7.3	0.003
2000	38	61	83	108	126	149	15.3	13.2	<0.001
2001	35	56	86	104	132	142	7.4	6.4	<0.001

* Use 'min' to compare means of treatments receiving fertiliser. Use 'mxmn' (max-min) to compare control with all other fertiliser treatments.

Table 13. Summary of N fertiliser responses at each site.

Site and harvest year	Optimum N rate (kg/ha)	Optimum yield (t/ha)
Gleadthorpe		
1999	183	7.14
2000	No opt	No opt
2001	135	5.17
Emley		
1999	No fit	No fit
2000	213	9.61
2001	229	8.25

Manure treatments

As would be expected, there were yield, grain N concentration and grain N off-take responses to the sludge applications in each year at both sites (except at Emley at the first harvest).

At Gt, harvest 1999, manure yields were significantly greater than the control (P<0.001). There were similarly highly significant effects of manure type (i.e. different manures producing different yields) and manure rate (not surprisingly). And there was also an interaction between manure rate and manure type, indicating that the nutrient supply from the different manures was different: some, especially YW2 and ST1, showed almost linear increases in yield with increasing N application rate, whereas others did not (Fig. 8). The same responses occurred with grain N concentration and grain N off-take.

At Gt, harvest 2000, there were two effects to separate in both the second and third harvest years: the residual effects of the 250N, 500N and 750N single treatments applied in autumn 1998 and the effects (residual plus fresh) from the 250N annual application. By running statistical tests in the absence of the yield data from the annual application treatment, it could be seen that the manures still carried a residual nitrogen effect in to the second year. There were yield increases above the control (significant at P<0.001). There were differences between manures, between rates of application and, again as in the first year, there was an interaction between manure type and rate. These data therefore provide conclusive proof of a residual nutrient effect beyond the first year and that there are differences between different types of manure. In this second year, there were no significant effects on grain N content but, because there were yield effects, these were carried through to grain N off-take. Consequently, the amounts of N removed in the grain were affected by manure rate and manure type.

Obviously, as would be expected, the yield and N off-take were largest from the plots that received fresh manure in the previous autumn. Thus, as an average of all manures, the yield and N off-take from an additional 250N application were larger than from a 750N application applied the previous year.

Yield effects at harvest 2001 were statistically analysed with and without the inclusion of the fresh applications made in autumn 2000. Excluding this treatment allowed us to test for residual effects three years after application. In summary, yields from treatments that had received manure three years previously still yielded more than the unfertilised control (P=0.008), proving conclusively that a small residual effect carried through to this third harvest. This effect was also noted with grain N off-take (P=0.007). Conversion of this yield increase to a fertiliser replacement value is discussed later.

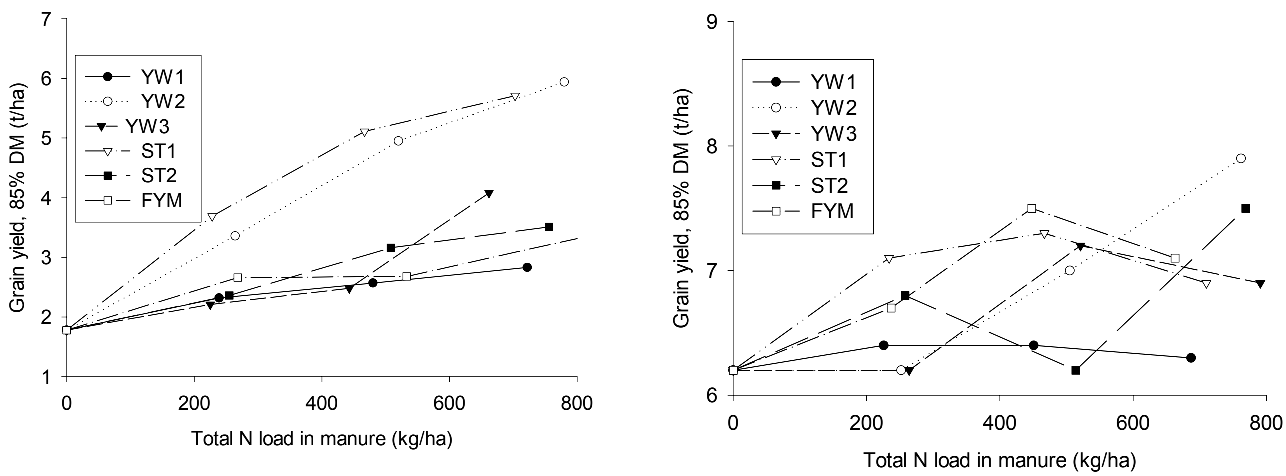


Figure 8. Yield response to manure N, 1999 harvest: Gleadthorpe (left) and Emley (right).

At Em, for harvest 1999, despite the lack of a fertiliser response, treatment effects from the manure applications were still apparent. Manure yields were significantly greater than the control (P<0.02). There were significant effects of manure type (i.e. different manures producing different yields, P<0.05), manure rate (P<0.01), and there was also an interaction between manure rate and manure type, indicating that the manures did not all increase yield with increasing application rate in the same manner (Fig. 8). There were similar responses with grain N concentration and grain N off-take.

As at Gleadthorpe, yield responses in the second and third years need to be separated to examine two separate effects: the residual effects of single applications of manure made in autumn 1998 (250N, 500N and 750N) and the effects of repeated applications of 250N each autumn.

Excluding the treatments receiving fresh manure showed that there were residual effects from the manures applied in autumn 1998 carried through into the second harvest year. Yields from the past manure treatments were significantly larger than the control (P=0.008). There were significant effects of manure type (P=0.007), manure rate (P=0.005) and an interaction between manure type and application rate. Thus, as at Gleadthorpe, the experiment provides clear evidence of residual nutrient value carried in to the second year, and that the residual effect depended on the manure type. Also, as at Gt, there were no consistent effects on grain N concentration in the second harvest year, but grain N off-take reflected the same trends as the yields.

At the final harvest (2001), there were significant differences in yields between the untreated control and the manure/sludge treatments (even excluding the fresh additions made the previous year), demonstrating that the residual effects from the manures carried into the third year at both Gt and Em. However, we were unable to distinguish between manure types, indicating that by this time all manures were behaving similarly in terms of N release.

Fertiliser replacement values

These were calculated from the yield responses for Gleadthorpe and Emley (Table 14). At Gt, we have the full three years of calculated Fertiliser Replacement Values (Table 14). The first year was missing from the Em site. An analysis of variance allowed us to find the main factors that affected FRV. These analyses were undertaken excluding the annual fresh application, and therefore relate to first year and residual effects.

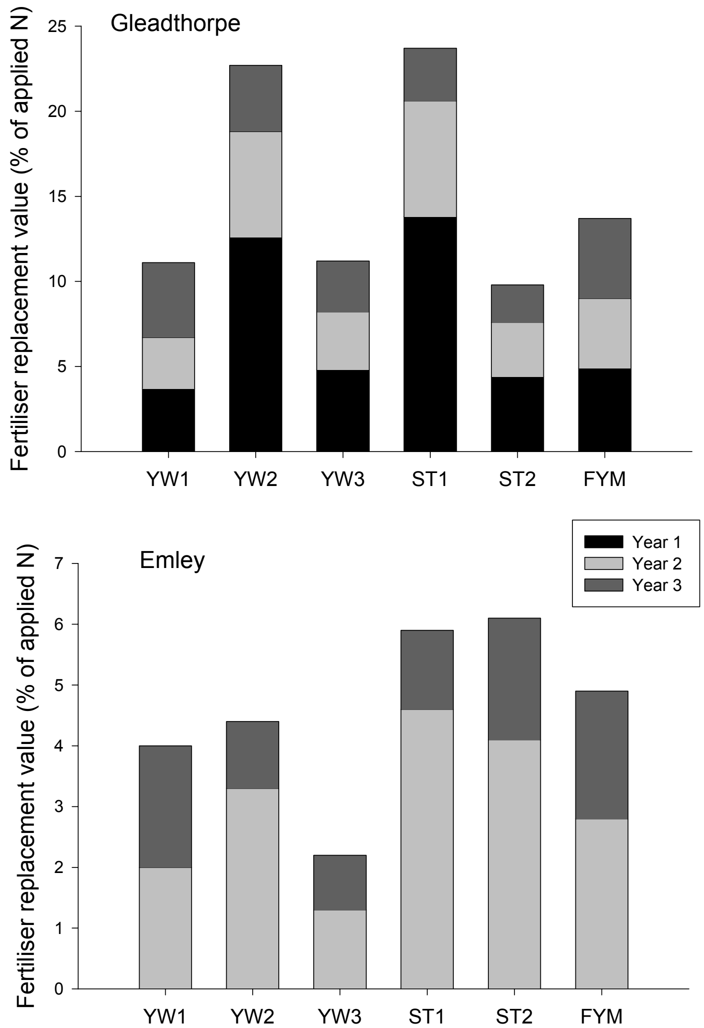


Figure 9. Summary of the FRV (% of applied N) for each manure/sludge over three years (Gt), and years 2 and 3 (Em).

At both the Gleadthorpe and Emley sites (summarised in Fig. 9), the following conclusions could be drawn about the main factors. The statistics were more robust for the Gt site, because this included data from all three years, whereas Em did not include year 1 (Table 14):

- Year – a highly significant effect (P=0.003 Gt or 0.04, Em) of application year on FRV, with the effect generally diminishing each year after application for the 'standard' sewage sludge cakes. However, there was also a year x manure interaction (P<0.001). This is because, particularly the composted manures, showed a fairly level FRV in each of the three years.

Table 14. Calculated N fertiliser replacement values by yield response (% of total N applied) for Gt and Em sites.

Year	Manure Type	Gleadthorpe 250N	Gleadthorpe 500N	Gleadthorpe 750N	Gleadthorpe **Mean**	Emley 250N	Emley 500N	Emley 750N	Emley **Mean**
1999	YW1	5.3	3.0	2.7	**3.7**				
	YW2	12.3	12.3	13.0	**12.6**				
	YW3	4.0	3.0	7.3	**4.8**				
	ST1	14	14.7	12.7	**13.8**				
	ST2	4.3	5.0	4.0	**4.4**				
	FYM	8.0	3.0	3.7	**4.9**				
Mean		8.0	6.8	7.2	**7.4**				
2000	YW1	3.3	3.3	2.3	**3.0**	2.3	2.0	1.7	**2.0**
	YW2	4.3	7.3	7.0	**6.2**	0.4	4.3	5.3	**3.3**
	YW3	2.7	3.3	4.3	**3.4**	1.7	1.0	1.3	**1.3**
	ST1	4.0	9.0	7.3	**6.8**	3.7	5.3	4.7	**4.6**
	ST2	2.3	4.0	3.3	**3.2**	5.3	2.0	5.0	**4.1**
	FYM	8.0	2.0	2.3	**4.1**	3.0	2.7	2.7	**2.8**
Mean		4.1	4.8	4.4	**4.5**	2.7	2.9	3.4	**3.0**
2001	YW1	7.3	3.7	2.3	**4.4**	3.0	1.3	1.7	**2.0**
	YW2	4.7	3.7	3.3	**3.9**	1.0	1.3	1.0	**1.1**
	YW3	3.3	1.7	4.0	**3**	1.7	0.7	0.3	**0.9**
	ST1	5.3	2.7	1.3	**3.1**	2.0	0.7	1.3	**1.3**
	ST2	2.3	2.3	2.0	**2.2**	3.0	1.0	2.0	**2.0**
	FYM	6.7	4.7	2.7	**4.7**	3	1.3	2	**2.1**
Mean		4.9	3.1	2.6	**3.6**	2.3	1.1	1.4	**1.6**
All years	YW1	5.3	3.3	2.4	**3.7**	2.7	1.7	1.7	**2.0**
	YW2	7.1	7.8	7.8	**7.6**	0.7	2.8	3.2	**2.2**
	YW3	3.3	2.7	5.2	**3.7**	1.7	0.8	0.8	**1.1**
	ST1	7.8	8.8	7.1	**7.9**	2.8	3.0	3.0	**2.9**
	ST2	3.0	3.8	3.1	**3.3**	4.2	1.5	3.5	**3.1**
	FYM	7.6	3.2	2.9	**4.6**	3.0	2.0	2.3	**2.4**
Mean		5.7	4.9	4.8	**5.1**	2.5	2.0	2.4	**2.3**

SEDs:

					Year	Rate	Manure	
SED	0.64	0.74	0.52		0.50	0.57	0.40	
DF	6	102	102		4	67	67	
	Y x M	Y x R	M x R	YxMxR	Y x M	Y x R	M x R	YxMxR
SED	1.33	0.98	1.28	2.25	0.88	0.68	0.98	1.44
DF	68	30	102	107	67	13	67	66
Same level of	Y	Y		Y	Y	Y		Y
SED (102 DF)*	1.28	0.91		2.22	0.80	0.56		1.39
				Y x M				Y x M
SED (102 DF)*				2.22				1.39
				Y x R				Y x R
SED (102 DF)*				2.22				1.39

*67 DF Em site.

- Manure Type – as would be expected, different manures showed highly significantly different sizes of FRV ($P<0.001$), with the 'standard' sewage sludge products having a larger FRV, particularly in the first year.
- Manure rate – no effect. The FRV (calculated as a proportion of applied N) was not affected by application rate. This is good, as it shows that the effect is a linear one. Within the range of N rates tested, doubling the application rate, for example, would also double the fertiliser value (in kg/ha).

Thus, in summary, the FRV of the organic materials can be split into 2 groups depending on the material type:

- 'Fresh' dewatered cakes and manures – larger FRV in the first year after application, with a diminishing return of about 50% of year 1 in year 2 and 50% of year 2 in year 3.
- 'Composted' materials - with a smaller FRV in year 1, but with a similar value in all three years.

Effects of manure P

Selected treatments were sampled and analysed to test for long-term soil effects. For each of the six manure types, soil samples (0-20 cm) were taken after harvest 2001 from treatments that received a single application of either 250 or 750 kg/ha N in the first autumn of the experiment. These were analysed for nutrients, organic matter and metal contents. Table 15 summarises the results for nutrients.

Gleadthorpe is a very sandy soil and it is generally noted that regular manure additions change the soil nutrient status in the short-term (e.g. Shepherd, 2001). Being sandy, the soil is poorly buffered and it is perhaps not surprising that the manure sludge treatments slightly reduced pH compared with the untreated control. This was presumably due to additions of N and S in the manure: these have an acidifying effect on reaction with the soil. The effect was not noted on the heavier textured Em soil.

Soils at both sites were well supplied with P before the start of the experiment. Sludges and manures are considered good sources of P. However, increases in soil P were not noted at Gt following applications of manures/sludges, but were noted at Em. The sludges are generally poor sources of K, whereas FYM has a large concentration of K and Mg. Consequently, there were significant increases in both soil K and Mg due to the additions in the FYM. Surprisingly, the manure/sludge treatments appeared to increase soil organic matter levels at Em, but this was not noted at Gt.

Table 15. Soil nutrient levels (0-20 cm) after the final harvest, 2001, for both sites (extractable nutrients, mg/kg, total N and organic matter, %). Control, 250N and 750N rates were sampled,

though only control and 750N are shown here. Start value = levels at the start of the experiment.

Start value		Treatment							Significant effects		
		Control	YW1	YW2	YW3	ST1	ST2	FYM	Control	Manure type	Manure rate
Gleadthorpe											
6.7	**pH**	6.7	6.7	6.4	6.5	6.5	6.3	6.6	0.01	0.02	-
38	**Ext P**	41	44	37	39	43	39	41	-	-	-
98	**Ext K**	93	99	84	100	90	93	146	-	<0.001	-
97	**Ext Mg**	85	84	71	92	79	77	96	-	<0.001	-
0.10	**Total N**	0.10	0.11	0.10	0.12	0.09	0.12	0.12	-	(0.07)	0.004
2.8	**Org. matter**	1.90	1.95	1.88	2.16	1.65	1.73	2.15	-	-	-
Emley											
7.0	**pH**	6.4	6.2	6.1	6.3	6.3	6.1	6.5	-	-	0.05
29	**Ext P**	34	44	43	38	39	42	35	0.04	0.01	<0.001
174	**Ext K**	237	223	245	225	235	207	313	-	0.002	-
286	**Ext Mg**	311	313	314	316	299	295	325	-	-	-
0.25	**Total N**	0.22	0.27	0.25	0.25	0.22	0.23	0.24	0.03	-	-
4.7	**Org. matter**	4.34	4.75	5.38	5.09	4.65	4.89	5.07	0.02	-	-

Effects of manure/sludge additions on crop P levels were small and generally statistically non-significant at Em (Table 16). Thus, any differences in crop uptake and removal from the field were directly related to yield level. At Gt, control values were slightly greater than the sludge/manure treatments in the first two years. This was probably due to a dilution effect in these treatments, which showed higher yields as a result of the applied N in the sludges.

Table 16. Summary of effects of manure sludge applications on grain P concentrations at harvest, comparing control against the average of all manure/sludge treated plots (%P in DM).

	Control	Manure/sludge	***P* value**
Gleadthorpe			
1999	0.40	0.37	0.008
2000	0.39	0.37	0.004
2001	0.37	0.37	0.747
Emley			
1999	0.31	0.33	0.207
2000	0.35	0.34	0.525
2001	0.36	0.37	0.633

Crop and soil metal effects

As for soil nutrients, soil samples (0-20 cm) were collected for metal analysis at the end of the experiment, at two rates of manure application: 250 and 750 kg/ha N (Table 17). Also shown is the soil metal content at the start of the experiment, which shows the good agreement between analyses at the start of the experiment and three years later on plots that received no manure/sludge inputs. The main point to note is the small effect of manure/sludge additions on metal concentrations.

Crop effects were quite consistent. The experiment tested a 'worst case' situation for grain metal concentrations. This is because sludge cakes and manures were added to the soil (potentially, sources of metals), but the crops did not receive additional fertiliser N. Therefore, the crops were lower yielding than if grown commercially with manure and fertiliser additions, and there would be less dilution of the metal in the grain without the additional yield from added fertiliser.

Despite this, effects on the grain concentrations of the metals were generally small. Table 18 shows the overall mean for all treatments at each site each year.

Table 17. Soil metal concentrations (0-20 cm) after the final harvest, 2001, for both sites (mg/kg). Control, 250N and 750N rates were sampled, though only control and 750N are shown here. Start value = levels at the start of the experiment.

Start value		Treatment							Significant effects		
		control	YW1	YW2	YW3	ST1	ST2	FYM	Control	Manure type	Manure rate
Gleadthorpe											
22	**Zn**	23	23	25	25	23	29	23	-	0.007	(0.07)
4.0	**Cu**	5.0	5.0	5.0	5.0	5.0	5.0	5.0	-	-	-
4.9	**Ni**	5.0	5.0	5.0	5.0	5.0	5.0	5.0	-	-	-
14	**Pb**	15	13	17	15	14	16	15	-	-	-
0.2	**Cd**	0.11	0.12	0.19	0.26	0.11	0.19	0.18	-	(0.07)	-
Emley											
62	**Zn**	96	100	97	101	100	107	94	-	(0.07)	0.003
27	**Cu**	27	32	25	28	29	31	27	-	-	0.004
17	**Ni**	17	18	16	17	18	17	17	-	0.05	-
49	**Pb**	47	48	52	46	49	51	46	-	-	-
0.3	**Cd**	0.66	0.67	0.74	0.56	0.78	0.61	0.64	-	0.04	-

Table 18. Average grain metal concentration at each site in each year (mean of all treatments), and an indication of significant treatment effects (‘<’ below analytical limit of detection).

Site &	Grain metal concentration (mg/kg)					
harvest	**Cr**	**Zn**	**Cu**	**Ni**	**Pb**	**Cd**
Gleadthorpe						
1999	<5	35	4.1	<1	<1	<0.1
2000	<0.2	30	3.5	<1	<1	<0.1
2001	<0.2	29	2.8	<1	<1	<0.1
Emley						
1999	<5	23	4.6	<1	<1	<0.1
2000	<0.2	18	4.1	<1	<1	<0.1
2001	<0.2	22	4.7	<1	<1	<0.1

At harvest 1999 (i.e. the harvest immediately after manure/sludge applications), concentrations of nickel and chromium were all below the analytical limit of detection. There was no effect on grain lead concentrations (average concentration 0.9 mg/kg at both sites). There was also no effect on grain cadmium at either site (average concentration 0.06 mg/kg). With copper, there were no effects at Emley (average concentration 4.5 mg/kg). The average concentration at Gt was similar at 4.2 mg/kg, though there was an effect of manure rate on this concentration: the copper concentration decreased, presumably due to dilution at higher yields. The largest effects were with zinc. At Em, manure type influenced grain concentration: the larger the concentration in the added manure, the larger the grain concentration. A similar relationship was found at Gt (Fig. 10), though concentrations were larger, presumably because the yield was smaller at Gt. As would be expected, rate of manure application also influenced grain zinc concentrations at Gt. This effect was not noted at Em.

In the second year, there were few effects of either manure applied two years previously or the fresh annual addition applied the previous autumn. There were no significant effects on grain concentrations of nickel, cadmium, lead or chromium (levels below or close to the analytical limit of determination). There was a small effect of manure type on grain copper at Gt, but not at Em. As in the previous year, the most effects were on grain zinc concentration (Fig. 10). There were effects of manure type at both sites, though the relationship between Zn applied in manure sludge and grain Zn concentration was only linear at Gt.

Similar effects were noted in the third year after application.

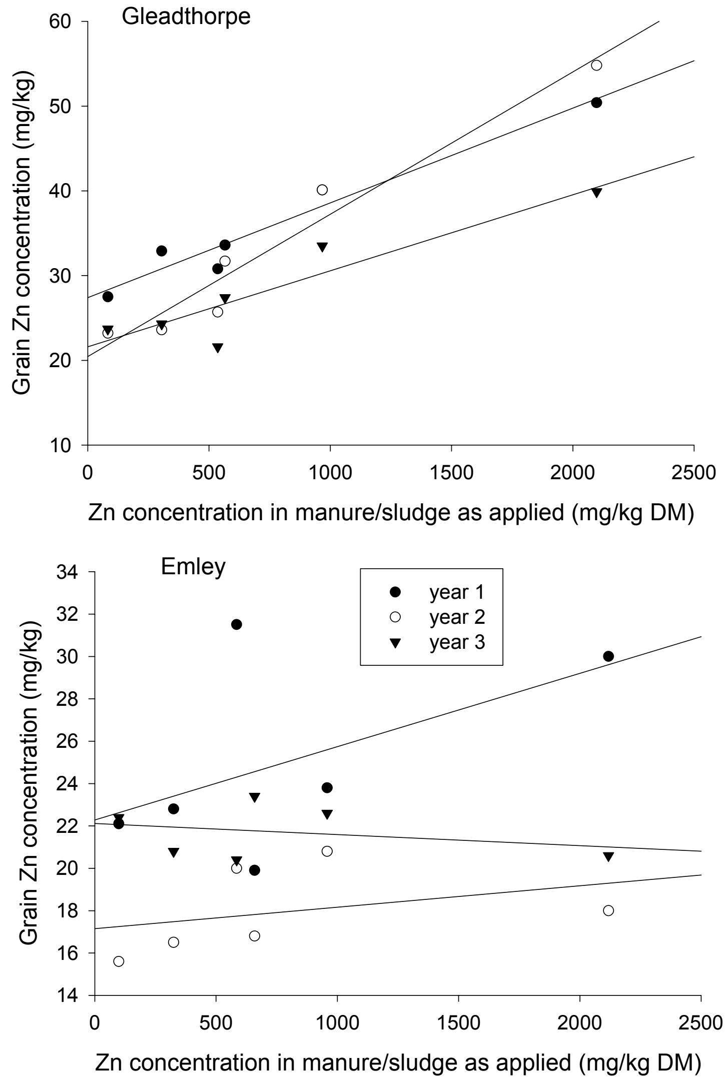


Figure 10. Relationship between manure/sludge Zn concentration (mg/kg DM0 and grain Zn concentration at each harvest(data for 750 kg/ha N application rate). Both were highly correlated at Gt (r^2 = 95%, 95% and 86% for years 1-3, respectively). At Em, there was only a significant relationship in year 1.

N leaching losses

Leaching data were collected from both sites over three years from three treatments: 250N annual applications, 500N and 750N single applications. Thus, in the first winter, the data allow examination of the effect on N leaching losses of six manures at three application rates. In the second and third winters, leaching losses from the residual effects of the 500N and 750N applications could be followed, as well as the effects of a repeated application at 250N. All could be compared with losses from an un-manured control.

In addition, supporting post-harvest soil Nmin data (measured on control, 250N and 750N treatments) provide further information on N leaching risk. This is because, generally, in the absence of fresh manure additions after soil Nmin has been measured, there is a strong linear relationship between Nmin and N leaching. This was clearly demonstrated for the 750N treatment (plus control) when Nmin was measured in autumn 1999 and compared with subsequent N leaching losses measured by the porous ceramic cups (Fig. 11). There was a linear relationship at Gt.

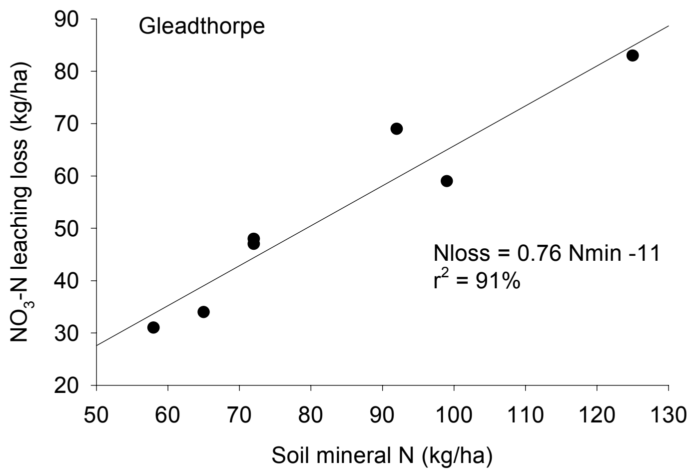


Figure 11. Relationship between autumn Nmin and subsequently leached N (autumn/winter 1999/2000)

Figures 12-13, show the NO_3-N concentration profiles at both sites for a single application at a rate equivalent to approximately 750 kg/ha N. Tables 19-20 summarise the total NO_3-N leaching losses each year, and the flow-weighted average N concentrations. For each year, the analysis of variance was undertaken for all treatments. In addition, in years 2 and 3, the analysis of variance was re-run excluding the 250N annual treatment, so that the residual effects of the single applications could be examined.

In winter 98/99 at Gt, there was 179 mm drainage during the autumn/winter period. Nitrate-N losses from the control treatment were 51 kg/ha (average N concentration 29 mg/l). Table 19 shows that in the first year there were highly significant effects of manure and of rate of application on N loss. Averaged over all application rates, losses were largest for YW3, due mainly to its relatively large NO_3-N content. As a proportion of the applied total N, losses were small, highlighting the small leaching risk from these materials.

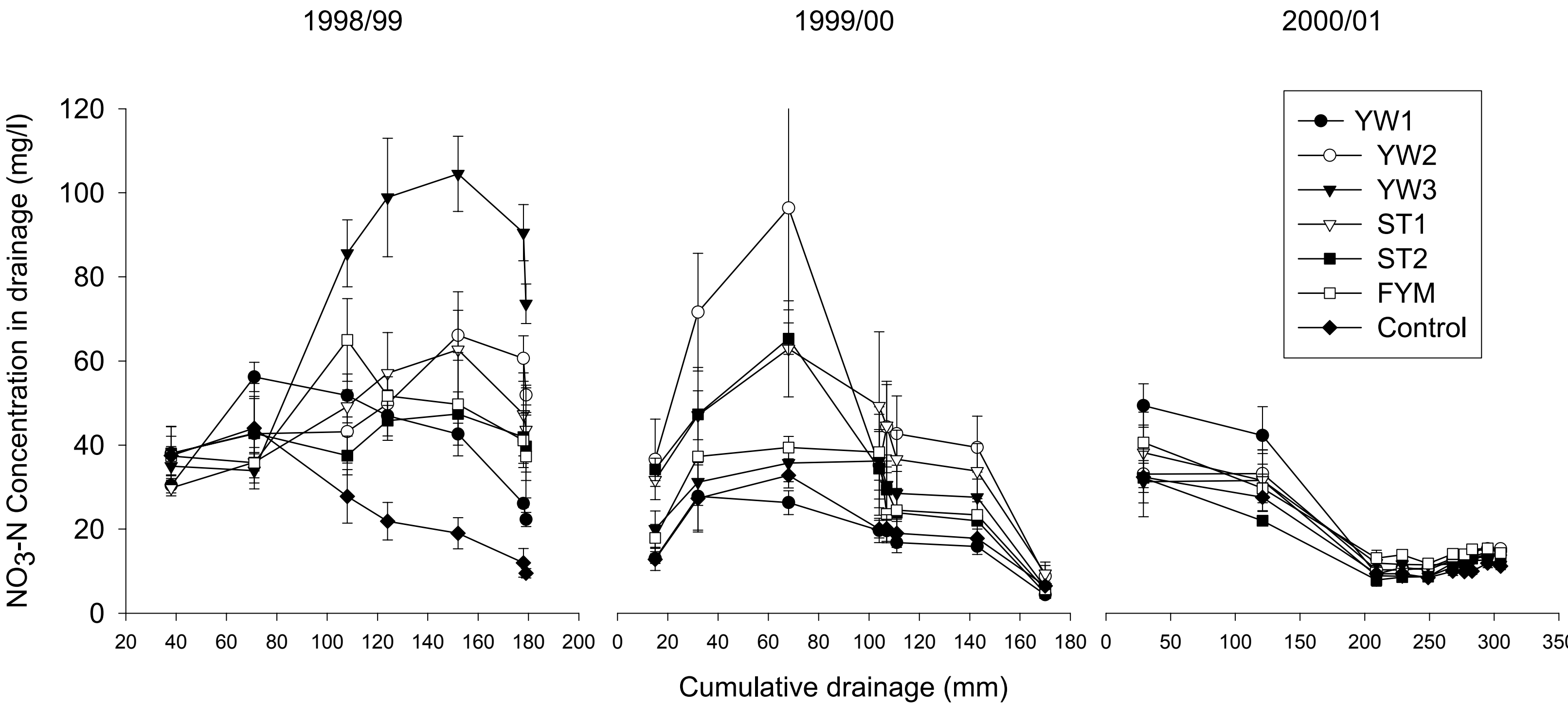


Figure 12. NO_3-N leaching profiles following a single application of FYM or sludge cake in autumn 1998: Gt site. Error bars denote standard errors.

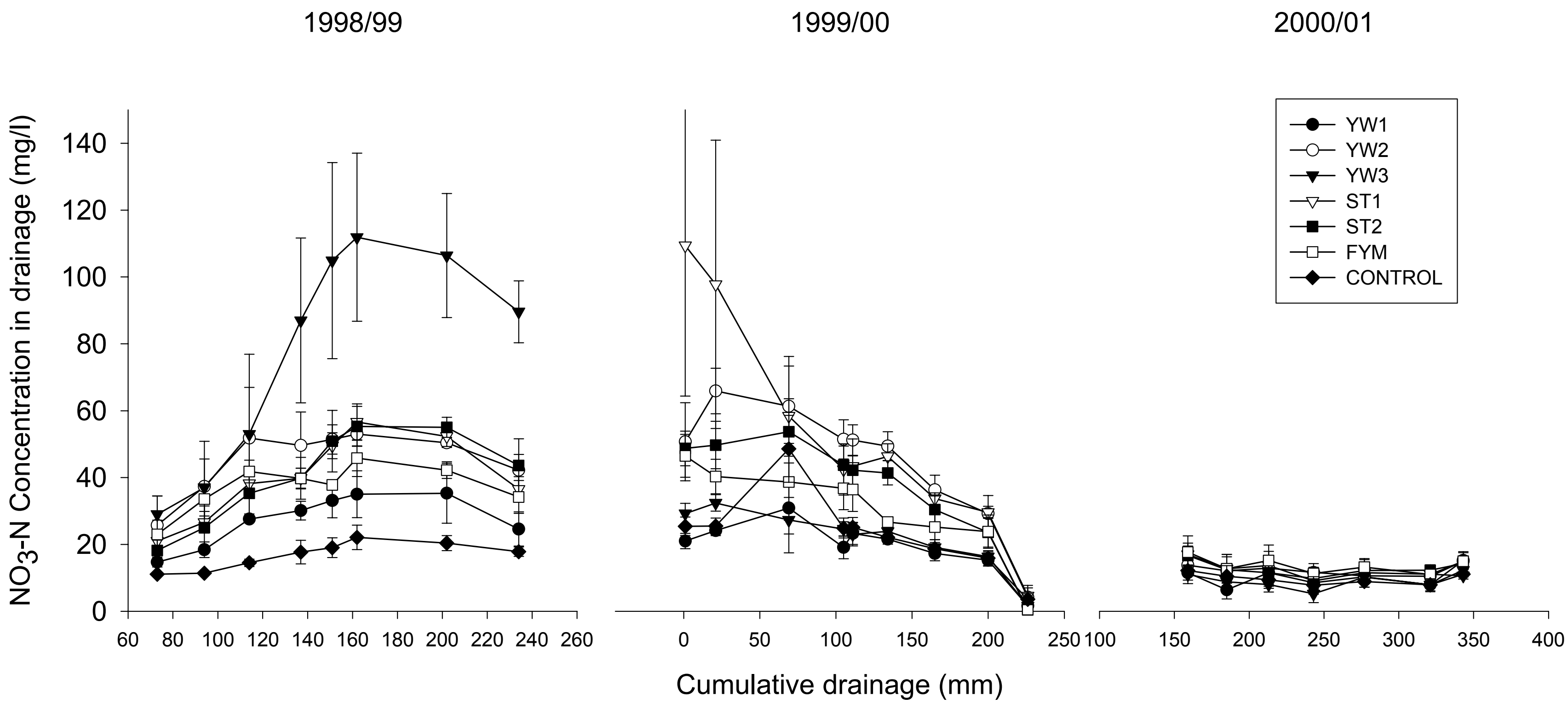


Figure 13. NO_3-N leaching profiles following a single application of FYM or sludge cake in autumn 1998: Em site. Error bars denote standard errors.

Table 19. Summary of measured NO_3-N leaching losses (Gt site). Concentration data not appropriate to be presented as an average of the three years.

Year	Manure type	NO_3-N loss (kg/ha) Control	250N	500N	750N	Mean	NO_3-N conc (mg/l) Control	250N	500N	750N	Mean
			Manure rate*					Manure rate*			
1998/99		51				51	28.6				28.6
	YW1		59	62	76	66		36.6	34.8	42.3	36.6
	YW2		69	81	87	79		44.2	45.4	48.7	44.2
	YW3		73	76	124	91		51.0	42.5	69.4	51.0
	ST1		77	72	81	77		42.9	40.2	45.4	42.9
	ST2		60	59	74	65		36.1	33.1	41.5	36.1
	FYM		55	73	83	70		39.3	40.7	46.6	39.3
Mean		51	66	71	88	73	28.6	41.0	39.5	49.0	41.0
1999/00		34				34	20.2				20.2
	YW1		44	32	31	36		26.0	18.7	18.1	20.9
	YW2		62	59	83	68		36.4	34.9	48.8	40.0
	YW3		57	39	47	48		33.8	22.7	27.5	28.0
	ST1		63	53	69	62		37.1	31.3	40.8	36.4
	ST2		54	41	59	52		32.0	24.4	34.8	30.4
	FYM		54	43	48	48		32.0	25.2	28.1	28.4
Mean		34	56	45	56	51	20.2	32.9	26.2	33.0	30.2
2000/01		53				53	17.2				17.2
	YW1		65	46	73	61		21.3	15	23.9	20.1
	YW2		94	58	61	71		30.9	19.1	20.1	23.4
	YW3		71	58	60	63		23.2	19	19.8	20.6
	ST1		94	70	58	74		30.8	23.1	19.1	24.3
	ST2		88	47	47	60		28.8	15.3	15.4	19.8
	FYM		82	91	64	79		26.8	29.8	21	25.8
Mean		53	82	62	61	67	17.2	27	20.2	19.9	22.1
All years		138				138					
	YW1		140	180	168	162					
	YW2		199	232	225	219					
	YW3		173	231	202	201					
	ST1		196	209	234	213					
	ST2		147	181	203	177					
	FYM		207	195	191	198					
Mean			177	205	204	192					

*NB 250N applied each year, 500N and 750N applied as single applications.

SEDs (All years only)

		Control	Type	Rate	T x R
SED	Max-min	18.6	20.9	19.6	
(36 DF)	Max rep		14.8	10.5	25.6

Figure 13 shows that there was, however, a residual effect from some of the manure treatments on soil Nmin in the following autumn after harvest of the first cereal crop (i.e. autumn 1999). There were significant effects of manure type (P=0.03) and manure rate (P=0.005) on soil Nmin to 90 cm in autumn 1999.

These differences in soil Nmin, were carried through to N leaching losses in winter 1999/00 (Table 19, Fig. 12). There was 170 mm drainage.

Figure 12 shows that concentrations were similar from all manure treatments by the end of the third winter after application.

Em, winter 98/99: this site was much wetter than Gt. There was 253 mm drainage during the autumn/winter period. Nitrate-N losses from the control treatment were smaller, however: 40 kg/ha (average N concentration 16 mg/l). Table 19 shows that, in the first year, there were highly significant effects of manure and of rate of application on N losses.

Table 20. Summary of NO_3-N leaching losses for the project (Em site). Concentration data not appropriate to be presented as an average of three years.

		NO_3-N loss (kg/ha)					NO_3-N conc (mg/l)				
			Manure rate*					Manure rate*			
Year	Manure	Control	250N	500N	750N	Mean	Control	250N	500N	750N	Mean
1998/99		40				40	16.0				16.0
	YW1		36	45	62	48		14.1	17.8	24.5	18.8
	YW2		46	55	103	68		18.1	21.9	40.7	26.9
	YW3		88	98	175	120		34.8	38.8	69.1	47.6
	ST1		73	64	92	76		28.8	25.5	36.2	30.2
	ST2		55	84	92	77		21.6	33.3	36.4	30.4
	FYM		59	66	86	70		23.4	26.1	33.9	27.8
Mean		40	59	69	102	75	16.0	23.5	27.2	40.1	29.5
1999/00		57				57	25.0				25.0
	YW1		60	43	44	49		26.7	19.2	19.6	21.8
	YW2		70	67	99	79		31.0	29.8	43.6	34.8
	YW3		66	46	48	53		29.0	20.3	21.1	23.5
	ST1		118	73	99	97		52.0	32.3	43.9	42.8
	ST2		71	61	82	71		31.5	26.8	36.2	31.5
	FYM		70	57	65	64		31.1	25.2	28.7	28.4
Mean		57	76	58	73	68	25.0	33.6	25.6	32.2	30.2
2000/01		36				36	10.5				10.5
	YW1		54	43	36	44		15.6	12.6	10.5	12.9
	YW2		50	39	44	44		14.5	11.4	12.7	12.9
	YW3		63	45	33	47		18.5	13.1	9.7	13.8
	ST1		57	41	48	49		16.6	12.0	14.0	14.2
	ST2		80	48	49	59		23.4	14.0	14.2	17.2
	FYM		38	38	52	43		11.2	10.9	15.1	12.4
Mean		36	57	42	44	47	10.5	16.6	12.4	12.7	13.7
All years		133				133					
	YW1		132	142	150	141					
	YW2		162	245	166	190					
	YW3		189	256	217	221					
	ST1		179	239	248	222					
	ST2		193	223	206	207					
	FYM		161	202	168	177					
Mean			169	218	192	190					

*NB 250N applied each year, 500N and 750N applied as single applications.

SEDs (All years only)

		Control	Type	Rate	T x R
SED	Max-min	15.2	17.1	16.0	
(36 DF)	Max rep		12.1	8.6	21.0

*NB 250N applied each year, 500N and 750N applied as single applications

As at Gt, averaged over all application rates, losses were largest for YW3, due mainly to its relatively large NO_3-N content. As a proportion of the applied total N, losses were quite small (Fig. 14), highlighting the small leaching risk from these materials.

A similar trend was observed as at Gt in the following winter, however. There was a residual effect from some of the manure treatments on soil Nmin in the following autumn after harvest of the first cereal crop. There were significant effects of manure type (*P*=0.03) and manure rate (*P*=0.005) on soil Nmin to 60 cm.

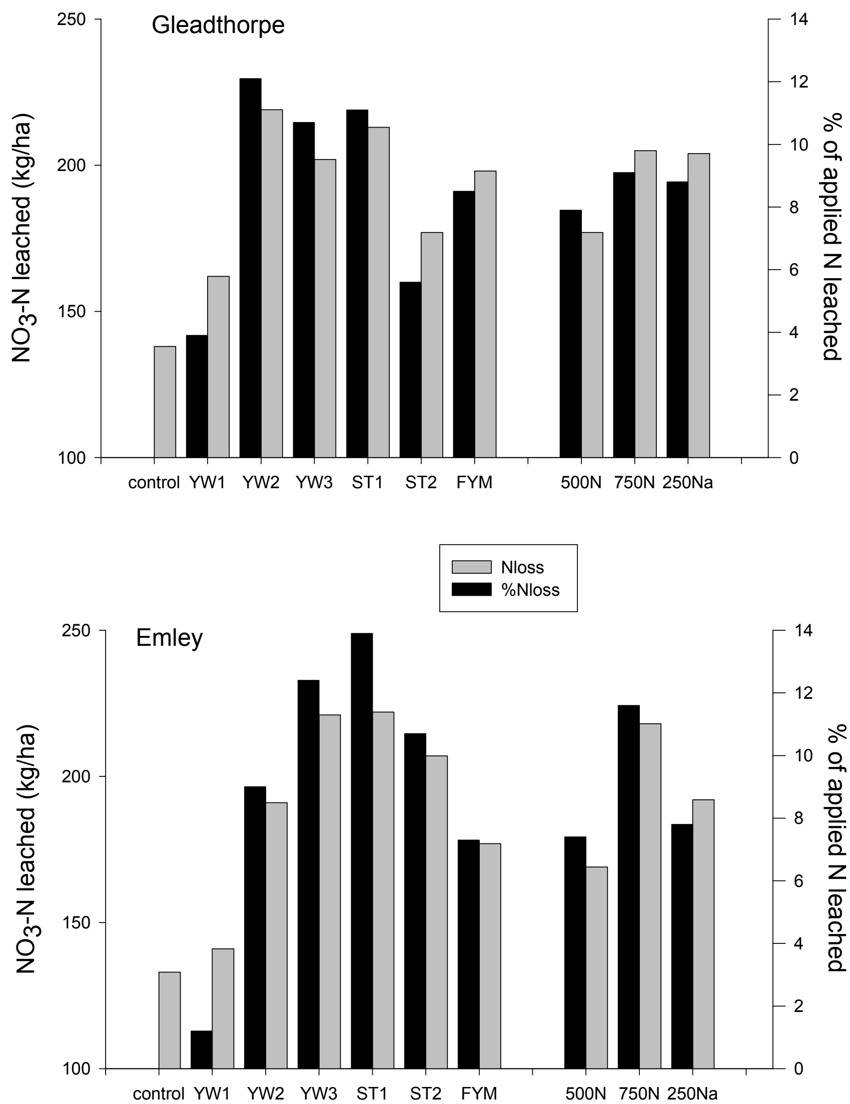


Figure 14. Nitrate-N leaching losses as a total of three years at Em and Gt sites. Data are presented as a mean of three application rates to show manure type effects, and as a mean of all manures at each application rate to show rate effects. Application rates were 500 and 750 kg/ha N as single applications or 250 kg/ha N in three successive autumns (250Na).

Nitrate-N leaching losses during winter 1999/00 (222 mm drainage) reflected these differences in autumn soil Nmin, with manure type, manure rate and manure-rate interaction effects (Table 20 and Fig. 12).

Autumn Nmin measurements (September 2000) showed that there were still residual effects from the manure treatments two years after application. These effects were reflected in N leaching losses in winter 00/01.

Total N losses over the three years are summarised in Figure 14. Data are summarised as a mean of three application rates (one-off applications of 500 or 750 kg/ha N and three annual applications of 250 kg/ha N), and as a mean of all manure sludges at the three same application rates. Results are expressed as kg/ha N leached and as a percentage of applied N.

Statistical analysis showed that there were highly significant differences between the control and manure/sludge treatments, as would be expected. There were also differences between manure types and between application rates. These trends were the same at both sites. In fact, N losses were almost the same at both sites, as an average of all treatments (190 vs 192 kg/ha for Em and Gt respectively).

The ranking of leaching losses was as would be expected from what we had learnt about the manures from their N response: leaching losses were generally larger from the 'fresh' uncomposted manures (YW3 and ST1). Also, because of YW3's relatively large nitrate content (arising from its composting), losses were large at Gt. Comparing total losses from a single application at 750 kg/ha N with three annual applications of 250 kg/ha N showed no differences at Gt, but significant differences at Em (Fig. 14).

5.1.2 Liquid manures

Background soil analysis

Potential sites were selected on the basis of past cropping and manuring history, with the aim of avoiding high residual fertility (N) situations and soil Nmin was measured across each site in the autumn, in order to confirm the anticipated low fertility status of the site (<100 kg/ha Nmin). Highest levels of SMN normally occur within the top 30cm of the profile, so even where data for the 30-60cm depth were missing, topsoil levels, taken together with the site history were sufficient to confirm site suitability (Tables 21 and 22).

Table 21. Chemical analysis of the topsoil at the experimental sites, 0-20 cm depth.

		Bridgets			Hattons		
		Oct 1998	Sept 1999	Aug 2001	Nov 1998	Oct 1999	Oct 2000
pH		8.0	8.1	7.6	7.8	6.7	*
Ext P	mg/l	23	18	26	58	43	*
Ext K	mg/l	131	112	162	120	94	*
Ext Mg	mg/l	31	-	39	-	49	*
Pb	mg/kg	8.7	17.8	26.8	90.0	42.0	*
Ni	mg/kg	25.2	18.4	19.1	20.4	15.4	*
Zn	mg/kg	83.3	51.0	77.0	405	175	*
Cd	mg/kg	1.59	1.47	1.43	0.88	0.81	*
Cr	mg/kg	31.6	21.0	28.5	64.9	40.9	*
Cu	mg/kg	13.5	12.7	13.1	67.3	28.9	*

* Late change in field site needed because of severe wet weather, no soil analysis data available.

Table 22. Initial soil Nmin (kg/ha) at the sites.

	0-30 cm	30-60 cm	Total to 60cm[1]
Bridgets			
1998/99	37	23	60
1999/00	na	na	na
2000/01	64	14	78
Hattons			
1998/99	14	-	14
1999/00	13	-	13
2000/01	29	-	29

[1] – SMN measurements available only 0-30cm at Hattons.
na – preliminary SMN measurements not available.

Manure nutrient characteristics and nutrient loading

The average analyses of the cattle and pig slurries (Table 23) are very closely aligned with typical nutrient contents for these materials (3.0, 1.2 and 3.5 kg/m^3 for N, P_2O_5 and K_2O content of cattle slurry at 6% DM; 4.0, 2.0 and 2.5 kg/m^3 for N, P_2O_5 and K_2O content of pig slurry at 4% DM) (Anon., 2000). Similarly, the NH_4-N content at 50% and 66% of total N content is close to typical for cattle and pig slurries, respectively. Liquid digested sludges typically contain c. 4% DM , 2.0 kg/m^3 N and 1.5 kg/m^3 P_2O_5 (Anon., 2000), values which are within the range represented by the sludges applied in this study. The analysis of digested liquid sludges is heavily influenced by the treatment processes of the plant and its management, though would normally be fairly consistent in material from a particular treatment works.

Table 23. Average analysis of slurries and liquid sludges at the two sites and across the four application timings, over 3 years (up to 24 samples) (fresh sample basis).

	Cattle slurry		Pig slurry		Liquid sludge LDS1		Liquid sludge LDS2	
DM %	5.90	(31)	3.66	(31)	3.77	(31)	2.38	(31)
Total N kg/m^3	3.13	(21)	4.17	(27)	2.68	(17)	1.81	(18)
NH_4-N kg/m^3	1.56	(25)	2.68	(21)	0.91	(19)	0.85	(12)
NH_4-N/N ratio	0.50	(16)	0.66	(15)	0.34	(20)	0.48	(18)
P_2O_5 kg/m^3	1.19	(22)	1.65	(48)	2.10	(35)	0.73	(45)
K_2O kg/m^3	3.18	(30)	3.66	(22)	0.31	(63)	0.27	(53)
Conductivity µscm^{-1}	11717	(34)	16743	(31)	4842	(25)	6036	(13)
No. of samples (n)	21		21		23		22	

Figures in brackets are the cv and represent standard dev/mean as %.

Table 24. Average and variability in rates of slurry and liquid sludge N applied at the two sites and across the four application timings, over 3 years (up to 24 samples).

	Cattle slurry		Pig slurry		Liquid sludge, LDS1		Liquid sludge, LDS2	
	N total	NH_4-N	N total	NH_4-N	N total	NH_4-N	N total	NH_4-N
Average kg/ha	111	55	109	72	116	40	126	60
Median kg/ha	113	54	109	71	115	39	127	59
Std. Dev.	18.5	10.8	9.9	11.3	18.2	9.9	21.7	6.5
cv %	17	19	9	16	16	25	17	11
min	67	38	89	54	78	20	78	50
max	146	73	126	96	157	62	180	77
No. of samples (n)	23		21		23		22	

Application rates for the slurries and sludges were based on preliminary sample analyses, with the aim of supplying a target rate of c. 120 kg/ha total N. Application rates therefore varied considerably, according to the analysis, ranging from 22 m^3/ha for pig slurry in 1998/99 to 77 m^3/ha for LDS2 in 2000/01. Whilst the average slurry/sludge N applied was close to the target for all four liquids (Table 24), the variability in the rates of N actually applied gives an indication of the difficulties in complying very closely with targets, essentially because of the variability in the analysis of these materials. It is clearly important that some check on the analysis of the N content of the material at application is available if confidence and precision in the use of slurry and liquid sludge N is to be achieved.

The slurries supplied, also, valuable rates of phosphate and potash, averaging 43 and 113 kg/ha P_2O_5 and K_2O, respectively, for cattle slurry and 41 and 98 kg/ha P_2O_5 and K_2O, for pig slurry. The liquid sludges supplied a higher rate of phosphate, 90 and 52 kg/ha P_2O_5 but a relatively low rate, 14 and 19 kg/ha K_2O, respectively, for the two sludge sources.

Manure metal content

Tables 25 and 26 show that metal concentrations in the manures were generally slightly above the average or median, but within the typical range for these types of manures and sludges in the UK (Nicholson *et al*., 1998). The metal additions via these materials therefore represent a realistic test of the negative aspects of metal loadings arising from their recycling on crops and soils.

Table 25. Average metal content of slurries and liquid sludges at the two sites and across the four application timings, over 3 years (up to 24 samples) - dry matter basis.

Metal	Cattle slurry		Pig slurry		Liquid sludge, LDS1		Liquid sludge, LDS2	
Zn mg/kg	348	(44)	846	(26)	943	(34)	1069	(53)
Cu mg/kg	113	(42)	625	(26)	788	(40)	298	(55)
Ni mg/kg	5.7	(61)	11.6	(82)	76.3	(37)	48.4	(69)
Pb mg/kg	5.1	(66)	11.4	(89)	112	(40)	148	(60)
Cd mg/kg	0.4	(57)	0.5	(63)	2.6	(55)	2.2	(100)
Cr mg/kg	11	(80)	17	(56)	91	(35)	207	(60)
No. of samples	*23*		*21*		*23*		*22*	

( ) Figures in brackets are the cv and represent standard dev/mean as %.

Table 26. Average metal content of slurries and liquid sludges at the two sites and across the four application timings, over 3 years (up to 24 samples) - fresh sample basis.

	Cattle slurry		Pig slurry		Liquid sludge, LDS1		Liquid sludge, LDS2	
DM %	5.90	(31)	3.66	(31)	3.77	(31)	2.38	(31)
Zn g/m^3	19.7	(34)	31.9	(44)	35.6	(36)	25.1	(54)
Cu g/m^3	6.4	(27)	24.2	(41)	30.0	(42)	6.8	(57)
Ni g/m^3	0.31	(42)	0.34	(45)	2.87	(38)	1.15	(71)
Pb g/m^3	0.32	(73)	0.35	(64)	4.20	(39)	3.42	(55)
Cd g/m^3	0.02	(53)	0.02	(66)	0.10	(55)	0.05	(68)
Cr g/m^3	0.55	(30)	0.50[1]	(-)	3.42	(35)	4.91	(60)
No. of samples (n)	21		21		23		22	

( ) Figures in brackets are the cv and represent standard dev/mean as %.
[1] Detection limit for Cr 0.5mg/l for methodology used.

Table 27. Crop grain yield response to fertiliser nitrogen application (r was fixed at 0.99).

Site	Year	Coefficients for linear plus exponential regression [1]				Precision of fit [2]	'Fitted' grain yield t/ha @ 85% DM	
		a	b	r	c		Control	240 kg/ha N
Ht	1999	9.56	6.25	0.99	0.004	89.3	3.3	9.9
	2000	10.56	5.97	0.99	0.015	68.4	4.7	6.4
	2001	0.88	3.40	0.99	0.013	95.2	5.5	11.8
Br	1999	5.25	2.66	0.99	0.018	92.7	2.6	9.3
	2000	10.26	6.84	0.99	0.010	94.7	3.5	7.4
	2001	8.18	3.96	0.99	0.013	98.0	4.2	10.9

[1] Linear/exponential curve fitted using : Yield = $a = b \times (r^N) + (c \times N)$.

[2] % variance accounted for in linear/exponential fit.

Grain yield, N off-take and Fertiliser Replacement Value

Fertiliser response

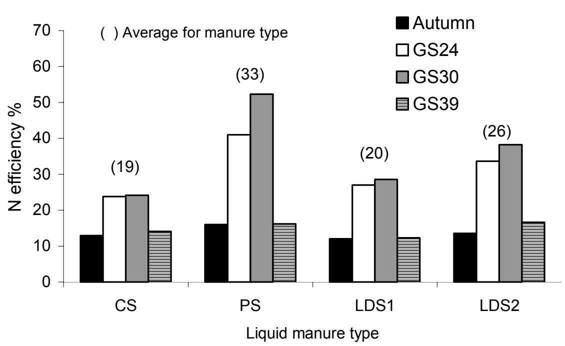
Experimental plots were established on low fertility sites (based on crop history and manure use and confirmed by SMN analysis) and all the wheat crops were responsive to fertiliser N (Table 27). A curve fitting procedure with a linear-exponential model successfully described the response, although the precision of fit was not always good. This was especially the case at the Hattons site in 1999/00 when wet weather and poor soil conditions throughout winter and spring delayed field operations and caused damage to the experimental plots.

Manures and fertiliser replacement value

Yields from the manure treatments were generally small, the result of sometimes wet weather, poor conditions and sometimes delayed treatments or damage to plots, and the sometimes low available N (manure analysis and N losses following application). Nevertheless, yields following application at GS24 and GS30 were elevated significantly (P<0.001) above those from autumn or GS39 treatment. Effects of manure type were less consistent but significant (P<0.05) in 4 out of 6 site-years.

Yield data were used by interpolation to estimate N efficiency (FRV) for all manure treatments. Highly significant differences (P<0.001) in FRV were apparent in 5 out of 6 site-years and, again in 4 out of 6 site-years there were differences (P<0.01) in FRV according to manure type, with pig slurry generally giving the highest efficiencies. These trends can been seen more readily in Figure 15, where the average FRVs (%) for all 6 site-years are presented. The effect of application timing is consistent across all manure types (Fig. 15a), and it can be seen (Fig. 15b) that efficiency for all manure types is similar, following both autumn and late spring (GS39) application. Although there was a trend towards increasing FRV with GS30 applications compared with GS24, differences reached statistical significance (P<0.001) only at Bridgets in 1999/00 and 2000/01 and this trend was actually reversed at Hattons (P<0.001) in 1999/00.

(a) Manure type and application time



(b) Application time and manure type

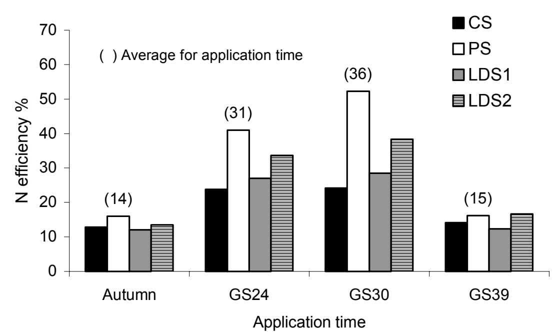


Figure 15. Nitrogen efficiency (FRV) of liquid manures compared to spring applied fertiliser N for grain yield, averages for the manures across the six site-years of data, 1998/99-2000/01, at Hattons and Bridgets

The apparent recovery of manure N in grain, expressed as a percentage of manure N applied was consistently lower than FRV based on the comparison of yield with fertiliser N response but the trend of increasing N recovery with later application timing, up until GS30 was consistent (Fig. 16a). Also, there were significant differences (P<0.001, or P<0.01) in each of the 6 site-years.

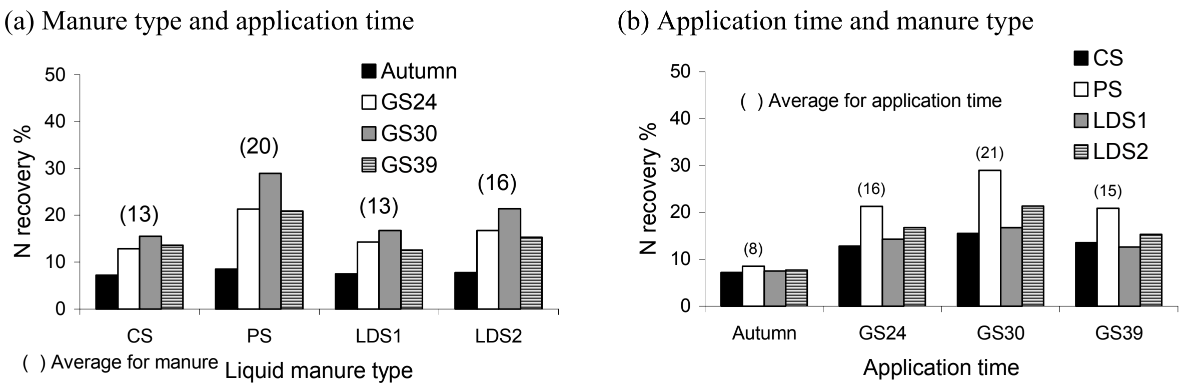


Figure 16. Apparent N recovery % (FRV) of liquid manures, averages for the manures across the six site-years of data, 1998/99-2000/01, at Hattons and Bridgets.

The calculated apparent manure N recovery was typically about 50% of the estimated FRV, N efficiency, across all application timings, sites and years, though increasing from about 35% from applications at GS24, to 50% for GS30 (Fig. 17) and up to about 85% for later applications at GS39. These data suggest that late spring slurry or liquid manure applications will tend to contribute relatively little to crop yield, but rather more to grain N content.

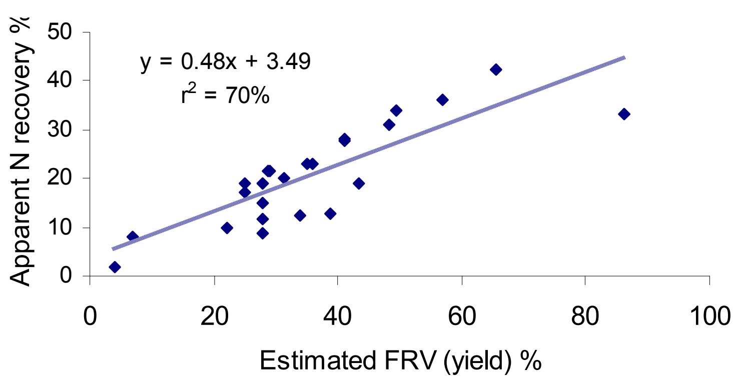


Figure 17. Comparison of apparent recovery % of liquid manure N with N efficiency (FRV) of liquid manures compared to fertiliser N for grain yield, averages for GS30 applications, six site-years of data, 1998/99-2000/01.

Effects of manure P

From site analyses data (Table 21), soil P status was satisfactory or good (Anon., 2000), such that, in cereals, crop yield response to freshly applied manure P would not be anticipated. In these circumstances, manure P will serve mainly to replenish crop P off-takes and maintain soil P status (Anon., 2000: i.e. RB209). The crop harvest data, which included grain P content and P off-take confirm this hypothesis. In no case was there any significant difference in grain P content with treatment, whilst grain P off-takes were significantly increased ($P<0.05$ or $P<0.001$) by applications at GS24 and GS30, as a result of the increased grain yield associated with these treatments. Grain P off-takes ranged from 6-16 kg/ha for control plots and up to a maximum of 24 kg/ha (55 kg/ha P_2O_5) across the manure treatments. In almost all cases, the manure P supply was able to meet crop off-take, usually with some surplus.

Crop and soil metal effects

Grain lead, nickel, cadmium and chromium were below (or else with insufficient sample numbers above) minimum laboratory detection limits (Pb >1.0; Ni >1.0; Cd >0.1; Cr >0.2 mg/kg, respectively) and therefore results could not be statistically analysed and are not presented in this report. In view of the generally low content of most of the metals in the manures, effects on the crop were expected to be slight, if present at all. The Cd content of all the manures was very low, leading to average applications of 0.7, 0.5, 4.2 and 3.3 g/ha of Cd in CS, PS, LDS1 and LDS2, with ranges of 0.3-1.6, 0.2-1.1, 0.4-10.7, 0.6-9.3 g/ha of Cd, respectively. Inputs of Pb, Ni and Cr, were also low, with averages (and ranges) for CS, PS, LDS1 and LDS2, respectively, as follows:

Pb - 11.1 (1.7-29.0), 9.8 (1.1-27.6), 177 (2.8-317), 244 (3.2-579);

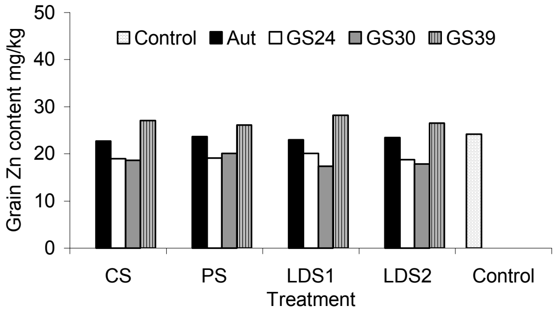
Ni – 11.2 (0.8-26.3), 9.8 (4.4-27.6), 121 (11.2-176), 83 (3.2-223);

Cr – 20 (16.5-43.8), 14 (11.1-23), 145 (32.5-247), 344 (32.1-750).

Zinc and copper content of the cattle and pig slurries were of a similar order to those of the liquid sludges and with Zn and Cu additions at agronomically significant levels, greater scope for crop effects was evident. Differences in grain Zn and Cu content, were apparent in 5 out of 6 site-years ($P<0.001$ or 0.05), most often in response to manure application timing. Examples of these results are presented in Figure 18. Grain Zn was typically around 20 mg/kg, with reduced levels ($P<0.001$) following manure applications at GS24 and GS30 (Fig. 18a). In some cases, the later GS39 application was associated with significantly elevated grain Zn ($P<0.001$) (Figs 18a and 18e). With copper, this pattern was replicated ($P<0.001$ or 0.05) in 3 out of 6 site-years (Fig. 18c). Often, Zn or Cu content of grain from the control (without manure or fertiliser treatment) was not significantly different from that of the manure treatments.

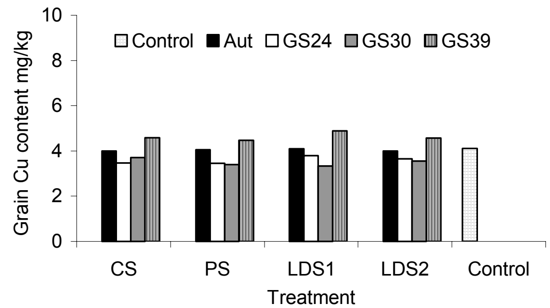
Grain Zn and Cu off-takes were more variable, with significant differences due to treatment in 5 out of 6 site-years for both metals. Grain off-takes were often elevated significantly ($P<0.05$ or <0.001) following application at GS24 and GS30 (Figs 18b, 18d & 18f) and less often as a result of different manure types. It is likely that both the increase in grain Zn and Cu off-take and the depression in grain Zn and Cu content associated with the early spring top dressing treatments, are the result of the increased manure N efficiency and the corresponding yield benefit. Whilst the elevation in metal off-take results from the increasing yield, this also appears to cause a dilution effect in terms of grain metal concentration.

(a) Grain zinc content (mg/kg), Bridgets 1999



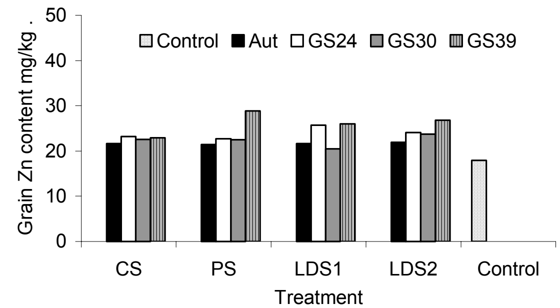
Differences due to timing significant (P<0.001)

(c) Grain copper content (mg/kg), Bridgets 1999



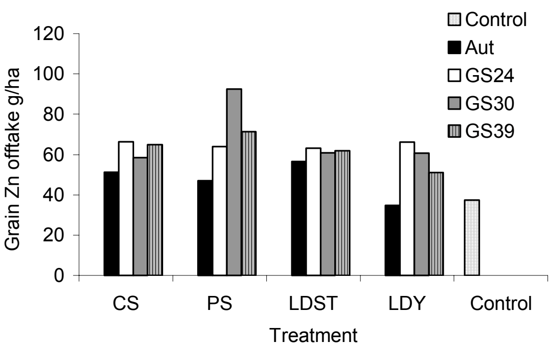
Differences due to timing significant (P<0.001)

(e) Grain zinc content (mg/kg), Hattons 2000



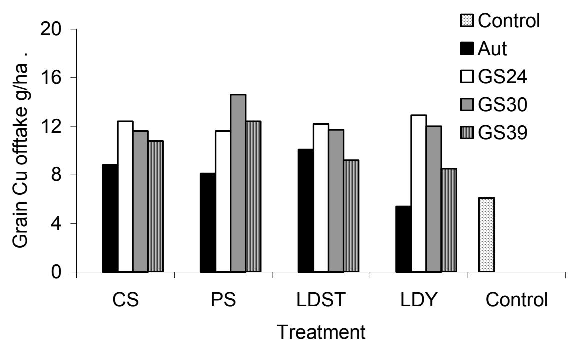
Differences due to timing significant (P<0.001)

(b) Grain zinc off-take (g/ha), Bridgets 1999



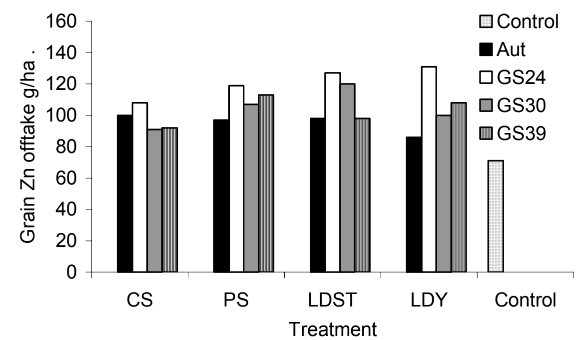
Differences due to timing significant (P<0.001)

(d) Grain copper off-take (g/ha), Bridgets 1999



Differences due to timing significant (P<0.001)

(f) Grain zinc off-take (g/ha), Hattons 2000



Differences due to timing significant (P<0.001)

Figure 18. Effect of liquid manure application type and timing on grain metal content and off-take: examples at Bridgets (1998/99) and Hattons (1999/00).

N leaching losses

Nitrate leaching losses from autumn manure applications was measured only at the Hattons site; the application of manures consistently increased N concentration in leachate samples, after the initial two sampling occasions. Drainage volume, following manure application in the autumn until the end of the sampling period in the spring, was estimated at 202 mm and 241 mm, respectively, for 1998/99 and 1999/00. The pattern of cumulative N leaching was fairly typical of the anticipated pattern with initially low losses early in the winter, and then more rapid losses with increasing drainage volume (Fig. 19).

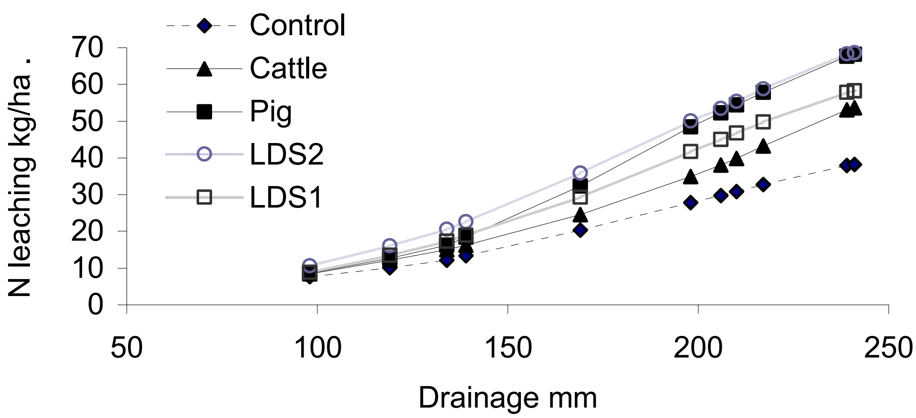


Figure 19. Cumulative nitrate leaching losses following autumn application liquid manures, Hattons 1999/00.

Table 28. Nitrate-N leaching loss following autumn application of manures at Hattons 1998/99 and 1999/00.

Treatment	N leaching loss 1998/99				N leaching loss 1999/00			
	kg/ha	% N applied	% NH_4-N applied	Conc. N (mg/l)	kg/ha	% N applied	% NH_4-N applied	Conc. N (mg/l)
Control	47.4	-	-	23.5	38.2	-	-	15.9
CS	56.0	10	16	27.7	53.6	11	29	22.2
PS	58.4	9	15	28.9	68.2	24	46	28.3
LDS1	60.5	11	25	30.0	58.2	16	51	28.5
LDS2	50.1	3	11	24.8	68.7	31	57	24.1
P value	0.18	-	-	0.18	0.18	-	-	0.18
s.e.d. ±	4.8	-	-		12.4	-	-	
d.f.	4	-	-	4	8	-	-	8

All the liquid manures contained a high proportion of readily available N (Table 23) and would be expected to be vulnerable to nitrate leaching on freely draining soils. Although estimated losses were consistently increased above those of the control, the differences failed to reach statistical significance

(P>0.05) in either of the two winter study periods (Table 28). In the final year, seedbed preparation, crop establishment and, hence, autumn manure treatments on the experimental site were precluded by the prolonged wet weather.

Soil Nmin levels, assessed on manure and control treatments post-harvest, were generally low and with no significant differences (P>0.05) between treatments, indicating no apparently increased risk of nitrate leaching following the manure applications in the succeeding winter. Examples of treatment means for two contrasting years are summarised in Figure 20.

(a) 1998/99 (b) 2000/01

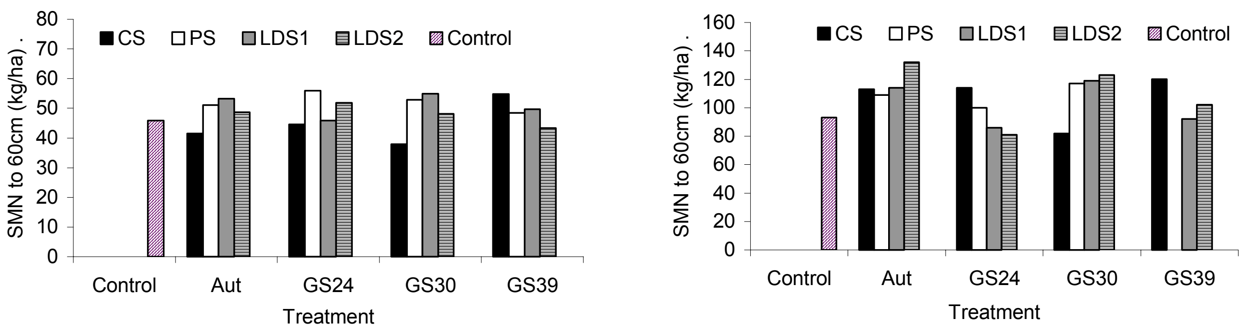


Figure 20. Comparison of post-harvest SMN to 60 cm depth on manure and untreated control plots. Results for two contrasting years at Bridgets, 1998/99 and 2000/01 (low and high background, respectively).

Ammonia volatilisation loss

There are many functions that could be used to describe ammonia flux. Slurry contains a finite amount of ammonia, which partitions itself between the liquid and gas phases. Part of the gaseous component is subsequently lost into the atmosphere thereby decreasing the NH_4-N content in the applied slurry. Thus, if the losses per successive unit of time are proportional to the slurry NH_4-N concentration, then one would expect a progressive increase in overall total ammonia loss with time in decreasing increments, which would reach a maximum at infinity. In practice, > 90% ammonia loss from slurry occurs over 5 days; Jarvis & Pain (1990). The Michaelis-Menten relationship between the observed reaction rate (v) at a substrate concentration [S] is now well known, such that $v = V[S]/(K_m+S]$, where V is the maximum reaction rate, K_m is the Michaelis constant and S is the total substrate. When $v = ½V$ then $K_m=S$.

The Michael-Menten equation may be written in the form shown below:

$N_{rate}(t, \Delta t) = N_{max} (K_m / ((t + K_m) \times (t + \Delta t + K_m))$

where

N_{rate} = ammonia flux kg/ha. h - for the period t to (t+Δt)

N_{max} = maximum potential ammonia loss as time approaches infinity

K_m = time at half N_{max}

t = time at start of monitoring period

Δt = duration of monitoring period

N_{max} and K_m were estimated, based on flux rates from monitoring periods only, using the Michaelis-Menten function for all treatment means. The Michaelis-Menten function was found to describe the cumulative emissions in the period following the application of liquid manures very well (Figs 21a-c).

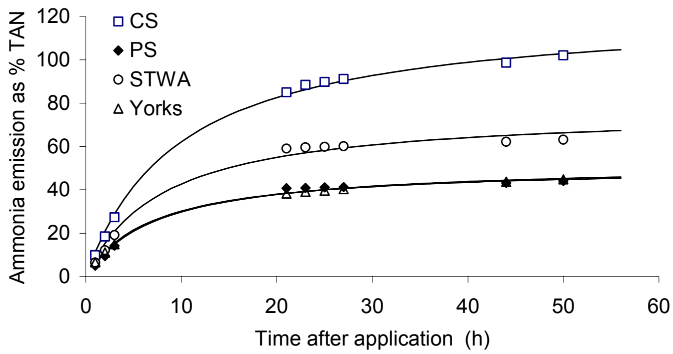
Table 29. Summary of cumulative ammonia losses following surface application of liquid manures at the Hattons site, at either GS24 or GS30; cumulative losses expressed as % of manure TAN applied, 1999-2001.

Manure type	1990		2000		2001	
	GS24	GS30	GS24	GS30	GS24	GS30
Final measurement, hrs	50.3	n.a	51.2	50.6	52.6	n.a
Cattle slurry	102.1	*	33.9	33.3	7.0	*
Pig slurry	44.2	*	49.3	29.5	1.0	*
LDS1	63.2	*	45.0	5.5	3.6	*
LDS2	44.8	*	42.7	14.9	-2.3	*
P =		-	0.178	0.034	0.32	-
s.e.d ±		-	6.09	7.09	4.53	-
d.f.	6	-	6	6	6	-

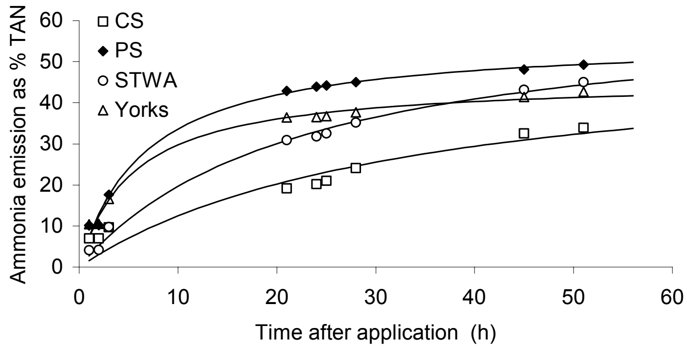
* Insufficient numbers of reliable laboratory analyses available – no results presented.

Although the shape of the fitted function and the relative proportion of applied TAN lost by volatilisation differed for the different manures, on different occasions, the differences were neither consistent nor, generally, significant. Total cumulative losses from the two sludges were significantly lower than from the slurries, at GS30, 2000 ($P<0.05$) (Fig. 21c, Table 29), on this occasion, possibly as a result of the lower DM content of the sludges. On two occasions (GS30, 1999; GS 30, 2001) a significant number of the diffusion samplers gave unreliable results, for instance where some of the chamber or ambient samples were recorded at less than the "blank" values, therefore no further analysis of that dataset was undertaken. Moreover, at GS24, 2001, only very low emissions were recorded over the three day monitoring period following treatment applications; very wet weather and low air temperatures (5ºC, during monitoring) are likely to have been the main contributory factors.

(a) GS24, 1999



(b) GS24, 2000



(c) GS30, 2000

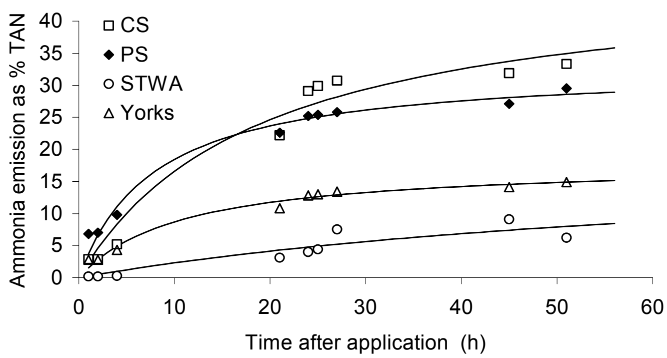


Figure 21. Ammonia losses following surface application of liquid manures at the Hattons site, at either GS24 or GS30; cumulative losses expressed as % of manure TAN applied. The points represent "actual" losses and the lines, the fitted Michaelis-Menten function.

5.2. Measuring N Mineralisation Potential (Laboratory Experiments)

5.2.1 Results: 1999 studies

Manure analysis

Drying the samples overnight at *c*. 30 °C removed most of the moisture with samples generally having a dry matter content of 90% or more (Table 30). The drying process also removed *c*. 50% of the ammonium content, though for two manures (ST2 and FYM), the amount was considerably less. The FYM in particular had a low ammonium content and it may be that there is a value below which incomplete drying cannot remove the ammonium because it is adsorbed to the organic matter.

Though we initially did not analyse for nitrate-N, the starting nitrate concentrations in the incubations suggested a large contribution from two of the manures (YW3 and FYM). This was subsequently confirmed by analysis of sub-samples of manure. The C:N ratios of the materials varied widely.

Table 30. Summary of analysis of fresh and dried manure samples, year 1.

	original samples					
Manure type	DM g/kg	Total N % SAR[1]	g/kg dry	NH_4-N mg/kg dry	NO_3-N[2] mg/kg dry	C:N[3] ratio
Dried samples						
YW1	933	2.08	22.3	171	6	11.6
YW2	924	2.87	31.1	129	58	8.3
YW3	914	2.36	2.8	140	2770	15.6
STW1	888	1.91	21.5	465	47	8.1
STW2	913	1.86	20.4	164	0	9.1
FYM	903	1.04	11.5	103	1880	11.6
Fresh samples						
YW1	267	0.6	22.5	331		
YW2	269	0.8	29.7	281		
YW3	369	0.84	22.8	222		
STW1	242	0.79	3.26	1070		
STW2	340	0.76	22.4	233		
FYM	472	0.54	11.4	135		

[1]Sample as received (i.e. expressed on fresh wt basis).
[2]Not measured in the manure - derived from the starting nitrate N concentrations in the incubation studies.
[3]Determined on separate samples.

Anaerobic incubations

The anaerobic incubations showed highly statistically significant differences (*P*=0.001) in N release between the manures, expressed as a proportion of the applied N (Table 31). The two manures with the highest starting nitrate concentrations (indicating considerable composting of these materials beforehand) were quite resistant to breakdown, mineralising only *c*. 3% of the applied N. In contrast, ST1 sludge mineralised 12% of applied N. The remaining manures fell between these two extremes. A Duncan's Multiple Range Test differentiated the manures into four groups (Table 31).

Table 31. Net N release from the anaerobic incubations over one week. Data have been normalised to take account of the variable N applications to each treatment, and also expressed as a percentage of the applied N. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

Manure type	NH_4-N start		NH_4-N end		NH_4-N change		Added N mg/kg	% Release	Duncan's test
	mg/kg	se	mg/kg	se	mg/kg	se	soil		
YW1	4.0	0.12	107.1	5.43	103.1	5.72	1180	7.8	b
YW2	9.1	0.36	170.4	2.76	161.3	2.09	1623	9.2	c
YW3	6.1	1.05	54.0	0.46	47.9	0.38	1341	2.7	a
ST1	15.0	0.59	157.9	7.22	143.0	8.69	1081	12.2	d
ST2	7.1	0.44	120.0	2.60	112.9	3.02	1054	9.6	c
FYM	1.8	0.02	34.4	1.30	32.5	0.64	590	3.6	a
Control	0.5	0.04	11.8	1.27	11.4	1.27			

Aerobic incubations

The net changes in Nmin (i.e. adjusted for control values) during the 16 week incubation were expressed as a percentage of applied N (Fig. 22) to allow comparison between the different treatments despite differential amounts of N being added.

Figure 22 shows considerable differences in the N release characteristics of the different manures. Two of the manures (the composted manures, as described earlier) showed little, if any, net N release and there was a tendency to immobilise Nmin.

The YW1 sludge showed only slight accumulation of soil Nmin. The remaining three manures showed a similar pattern of N release, though the quantities differed. All three showed a rapid release in the early weeks followed by a more gradual change: the classic two phase mineralisation process.

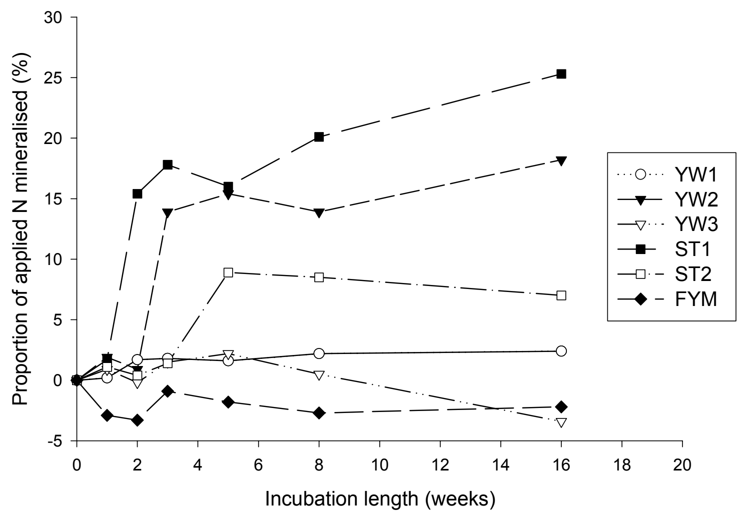


Figure 22. Change in mineralised N with time, expressed as a proportion of the N applied in manures/sludges: second incubation series (2000).

There were highly statistically significant differences (*P*=0.001) between the manures in the amounts N released over the 16 week period, expressed as a proportion of the applied N. A Duncan's Multiple Range Test separated the manures into five categories at the end of the 16 week incubation (Table 32). Figure 22 shows that although this ranking generally appeared consistent throughout the incubation period, analysis of individual periods shows that the Duncan's test produced some variations in ranking, depending on the length of the incubation period, confirmed in Table 33.

Table 32. Net N release from the aerobic incubations over 16 weeks. Data are expressed as a percentage of the applied N. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

Manure	N release % of applied N	Duncan's
YW3	-3.3	a
FYM	-2.2	a
YW1	2.4	b
ST2	7.0	c
YW2	18.3	d
ST1	25.3	e

Table 33. Ranking of manures according to length of aerobic incubation. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

N release ranking	Incubation period (weeks) 1	2	3	5	8	16
LEAST	FYM a	FYM a	FYM a	FYM a	FYM a	YW3 a
	YW1 b	YW3 b	ST2 b	YW1 b	YW3 b	FYM a
	YW3 bc	ST2 b	YW3 b	YW3 b	YW1 b	YW1 b
	ST2 bc	YW2 b	YW1 b	ST2 c	ST2 c	ST2 c
	YW2 c	YW1 b	YW2 c	YW2 d	YW2 d	YW2 d
MOST	ST1 c	ST1 c	ST1 d	ST1 d	ST1 e	ST1 e

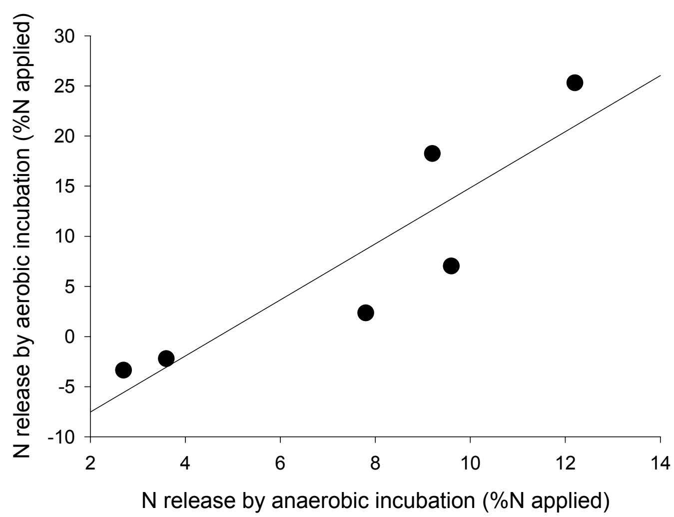


Figure 23. Relationship between N released by aerobic and anaerobic incubations (1999). Correlation coefficient, r, has the value 0.89.

There was a strong correlation between N release by anaerobic and aerobic incubation (Fig. 23). The anaerobic incubation liberated *c.* 2.5 times as much N as the aerobic method.

5.2.2 Results: 2000 studies

Manure analysis

Drying the samples overnight at *c.* 30 ^{o}C removed most of the moisture with samples generally having a dry matter content of 85-90% (Table 34). Unlike in the first year, the drying process did not remove most of the ammonium content. Consequently, starting levels of 'readily available N' differed considerably between treatments at the start.

Starting nitrate concentrations were also large for the three YW sludges and the FYM. This was to be expected from YW1 and YW3 (composted) and the FYM – but it was perhaps more surprising for the YW2 sludge, a standard dewatered cake. The C:N ratios of the materials varied widely.

Table 34. Summary of analysis of fresh and dried manure samples, year 2.

Manure type	original samples DM g/kg	Total N % SAR[1]	Total N g/kg dry	NH$_4$-N mg/kg dry	NO$_3$-N mg/kg dry	C:N ratio
dried samples						
YW1	851	1.91	22.5	153	1700	20.6
YW2	883	3.27	37.0	1820	2600	23.8
YW3	811	2.30	28.4	825	3000	31.0
STW1	856	3.96	46.3	1400	110	6.5
STW2	855	3.04	35.5	1850	88	14.2
FYM	956	1.24	13.0	96.1	2200	26.1
fresh samples						
YW1	282	0.63	22.3	190	1800	19.3
YW2	263	0.88	33.4	2757	2500	8.6
YW3	345	0.90	26.2	86	3200	10.8
STW1	186	0.96	51.4	9070	45	6.0
STW2	254	0.84	33.1	1432	55	8.0
FYM	548	0.80	14.5	49	2200	10.6

[1]Sample as received (i.e. expressed on fresh wt basis).

Table 35. Net N release from the anaerobic incubations over one week. Data have been normalised to take account of the variable N applications to each treatment, and also expressed as a percentage of the applied N. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

Manure type	NH$_4$-N start mg/kg	se	NH$_4$-N end mg/kg	se	NH$_4$-N change mg/kg	se	Added N mg/kg soil	% Release	Duncan's test
YW1	6.4	0.82	104.7	9.56	98.3	8.89	1140	6.7	ab
YW2	206.9	11.13	310.0	12.63	103.1	9.73	1945	4.2	a
YW3	50.6	7.53	128.5	9.36	77.9	11.16	1371	4.1	a
ST1	340.8	15.81	594.7	34.89	253.9	41.98	2359	9.9	c
ST2	231.6	23.19	407.2	23.65	175.6	36.81	1807	8.5	bc
FYM	3.3	0.10	62.9	3.54	59.6	3.63	740	5.1	a
Control	2.2	0.85	23.7	0.81	21.5	1.39			

Anaerobic incubations

The anaerobic incubations showed statistically significant differences (*P*=0.02) in N release between the manures, expressed as a proportion of the applied N (Table 35). Absolute amounts of N released by anaerobic incubation were similar to the first year (0-10%), which demonstrates that the method is repeatable. However, trends were not as easily discernible as in the first year. ST1 was identified as the sludge with the most mineralisable organic fraction (in agreement with year 1), but the test did not identify YW2 as a 'high mineraliser'. As in the first year, ST2 was also identified as a sludge with a more labile organic fraction.

Aerobic incubations

The net changes in soil Nmin (i.e. adjusted for control values) during the 16 week incubation were expressed as a percentage of applied N (Fig. 24) to allow comparison between the different treatments despite differential amounts of N being added. Figure 24 shows considerable differences in the N release characteristics of the different manures. Absolute amounts of N released by anaerobic incubation were similar to the first year (0-10%), which demonstrates that the method is repeatable. Two of the manures (YW3 and FYM) showed a substantial decline in Nmin between weeks 8 and 16, suggesting re-immobilisation of N in these treatments. Both had previously been identified as slow release sources. YW2 sludge released the most N, in agreement with field experience in the first year. Table 36 shows the final rankings for organic N release after 16 weeks: Table 37 shows that this ranking order changed depending on length of incubation.

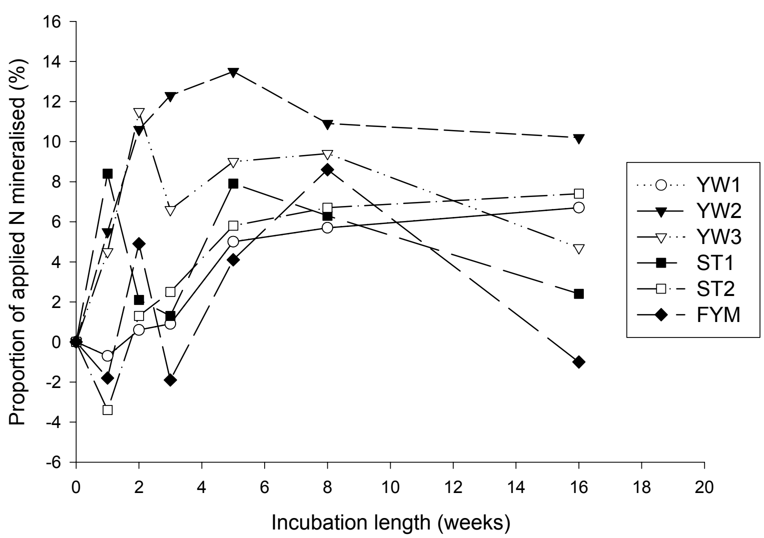


Figure 24. Change in mineralised N with time, expressed as a proportion of the N applied in manures/sludges: second incubation series (2000).

Table 36. Net N release from the aerobic incubations over 16 weeks. Data are expressed as a percentage of the applied N. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

Manure	N release % of applied N	Duncan's
FYM	-1.0	a
ST1	2.4	ab
YW3	4.7	b
YW1	6.7	bc
ST2	7.4	bc
YW2	10.2	c

Table 37. Ranking of manures according to length of aerobic incubation. A Duncan's Multiple Range Test was also used to differentiate between the manures. Means with the same letter are not significantly different at *P*=0.05.

N release	Incubation period (weeks)					
ranking	1	2	3	5	8	16
LEAST	ST2 a	YW1 a	FYM a	FYM a	YW1 a	FYM a
	FYM ab	ST2 a	YW1 ab	YW1 a	ST1 a	ST1 ab
	YW1 abc	ST1 a	ST1 ab	ST2 a	ST2 a	YW3 b
	YW3 bcd	FYM ab	ST2 ab	ST1 ab	FYM a	YW1 bc
	YW2 cd	YW2 b	YW3 b	YW3 ab	YW3 a	ST2 bc
MOST	ST1 d	YW3 b	YW2 c	YW2 b	YW2 a	YW2 c

Unlike in the previous year, there was not a strong correlation between N release by anaerobic and aerobic incubation.

5.2.3 NIRS

In both years, similar results were found from scanning the manure samples. Spectra showed peaks in the 1500 nm and 2000 nm regions. The 1100-2500 nm range is the near infra red and gives information on the bending and stretching of chemical bonds – in this case the OH bonds. The spectra were shifted up and down, and this was due to differences in particle size and silica content.

The spectra were treated to single non variant and detrending in order to remove differences due to particle size and silica content. The spectra correlated well against laboratory determinations of DM (r=0.91) and total N (r=0.94). Correlations were also good for NH_4-N (r=0.69) and NO_3-N (r=0.84).

However, no correlation was found with the N release from either aerobic or anaerobic incubations. This may have been because the dataset was too small.

5.3. Results from Large Plots (Demonstration Sites)

Demonstration studies were successfully completed at two sites during 2000; at The Old Hattons Farm, Coven, Staffs and at Hornby Castle, Bedale, N Yorks.

Correct estimation of the contribution from manures is an important factor in the efficient and economic use of fertiliser N and the achievement of satisfactory crop response. The treatments selected for the two sites are shown below, with further details of plot layout and demonstration site plan for the Hattons, in Figure 25:

	Hattons, Coven	Bedale
1.	Liquid digested sludge, spring, 50m^3/ha - broadcast	Liquid digested sludge, spring, 50 m^3/ha - broadcast
2.	Liquid digested sludge, spring, 50m^3/ha - trailing hose	Liquid digested sludge, spring, 75 m^3/ha - broadcast
3.	Pig slurry, spring, 50 m^3/ha - broadcast	Pig slurry, spring, 25 m^3/ha - broadcast
4.	Dewatered cake, autumn, 32 t/ha	Dewatered cake, autumn, 30 t/ha
5.	Cattle FYM, autumn, 60 t/ha	Cattle FYM, autumn, 30 t/ha
6.	No manure (fertiliser only)	No manure (fertiliser only)

Manure application rates and timings and estimated harvested yields are summarised in Table 38 for Hattons. At the Hattons, grain yield of the manure-fertiliser combinations appeared to be lower than the conventional fertiliser-only treatment, based on the assessments from these unreplicated plots. However, this was attributed to a fertility trend E-W, across the site from plot 1 (autumn FYM) to the fertiliser N (plot 6), at the lower W end of the site. The field was situated on terrace deposits of a river valley and detailed soil examination across the site revealed an increasing depth of topsoil moving from E to W and closer to the river. The detailed sample harvest yields taken by the plot combine (see surface plots, Figs 26a-f) indicated, in most cases, a yield depression at the E side of the plot, corresponding to the occurrence of the tramline within harvest strip 5. There appeared similar, though less consistent, evidence of a yield depression at the W side of the plot, coinciding with the extra, manure top-dressing wheeling.

Yields assessed by GPS combine at the Bedale site, summarised in Figure 27. and in Table 39 suggested no yield penalty associated with the integrated manure and fertiliser plots, despite the reduced fertiliser N inputs

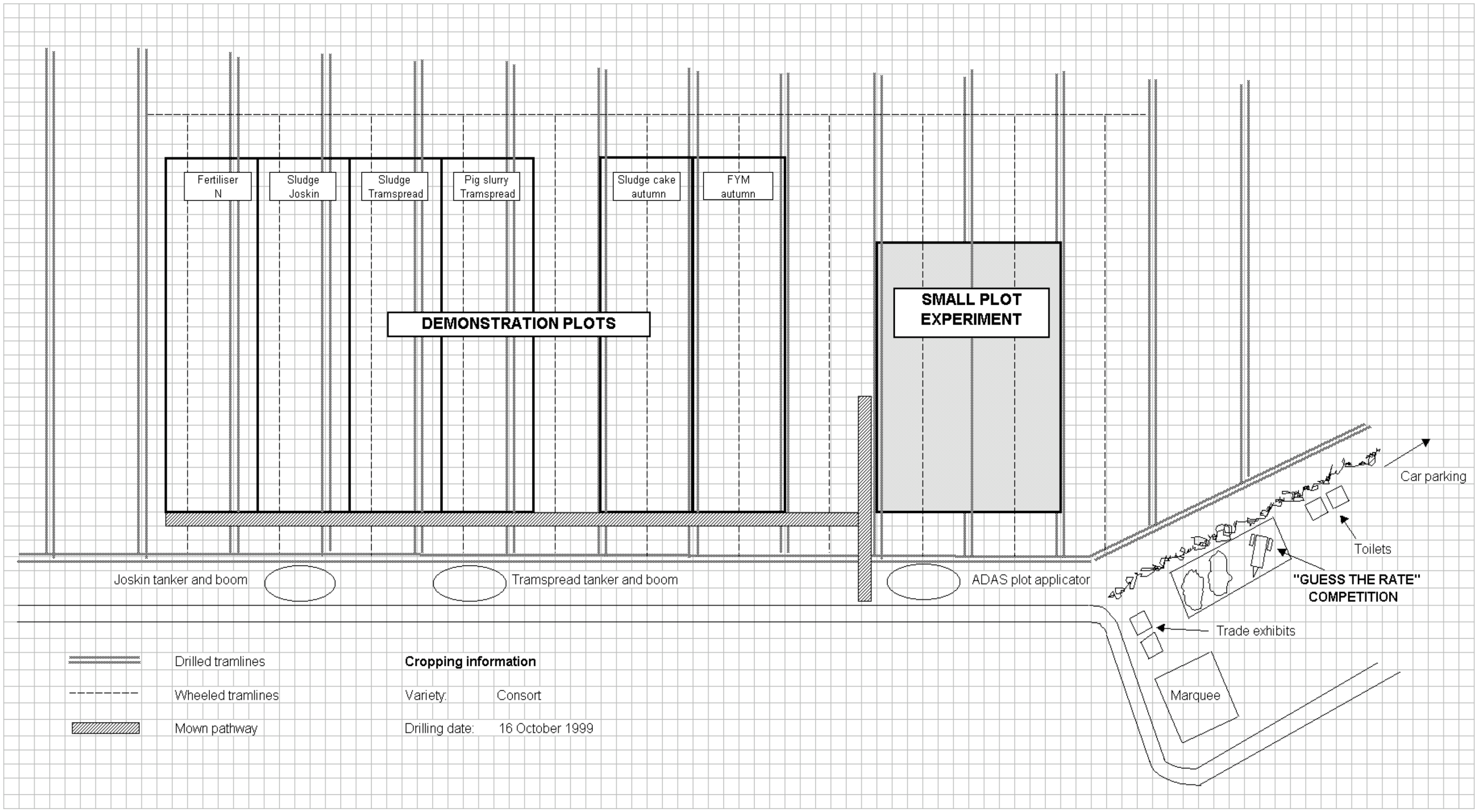


Figure 25. Demonstration site layout, Hattons, 2000; showing treated area of demonstration plots.

Table 38. Manure and fertiliser N treatments applied to demonstration plots at the Hattons site, 2000; with estimated plot yields by integration of small harvested sub-plots taken by plot combine.

		Manure application		**a**	**b**	**c**	
Treatment	Application date	Application rate	Total N applied as manure kg/ha	Estimated manure N available[1] kg/ha	Fertiliser N GS 24 kg/ha	Fertiliser N GS30[2] kg/ha	Grain yield t/ha
FYM, autumn	22 Sept.'99	60 t/ha	343	35	40	135	6.9
Sludge cake, autumn	22 Sept.'99	32 t/ha	278	25	40	145	6.7
Pig slurry, spring, surface broadcast (Boom & splashplate)	22 Mar. '00	50 m^3/ha	243	110	40	60	6.8
Liquid sludge, spring, surface broadcast (Boom & splashplate)	22 Mar. '00	50 m^3/ha	108	45	40	125	7.2
Liquid sludge, spring, trailing hose (Surface band)	22 Mar. '00	50 m^3/ha	107	35	40	135	7.3
Fertiliser N[3]	13 March & 5 May '00	-	-	-	40	170	7.9

[1] Estimated making allowance for losses due to N leaching, ammonia emissions, using MANNER.

[2] Fertiliser application at GS 30 (col. c) adjusted to give N equivalent to standard recommended = cols. a + b + c (210 kg/ha).

[3] Fertiliser N application according to standard recommendations (RB209).

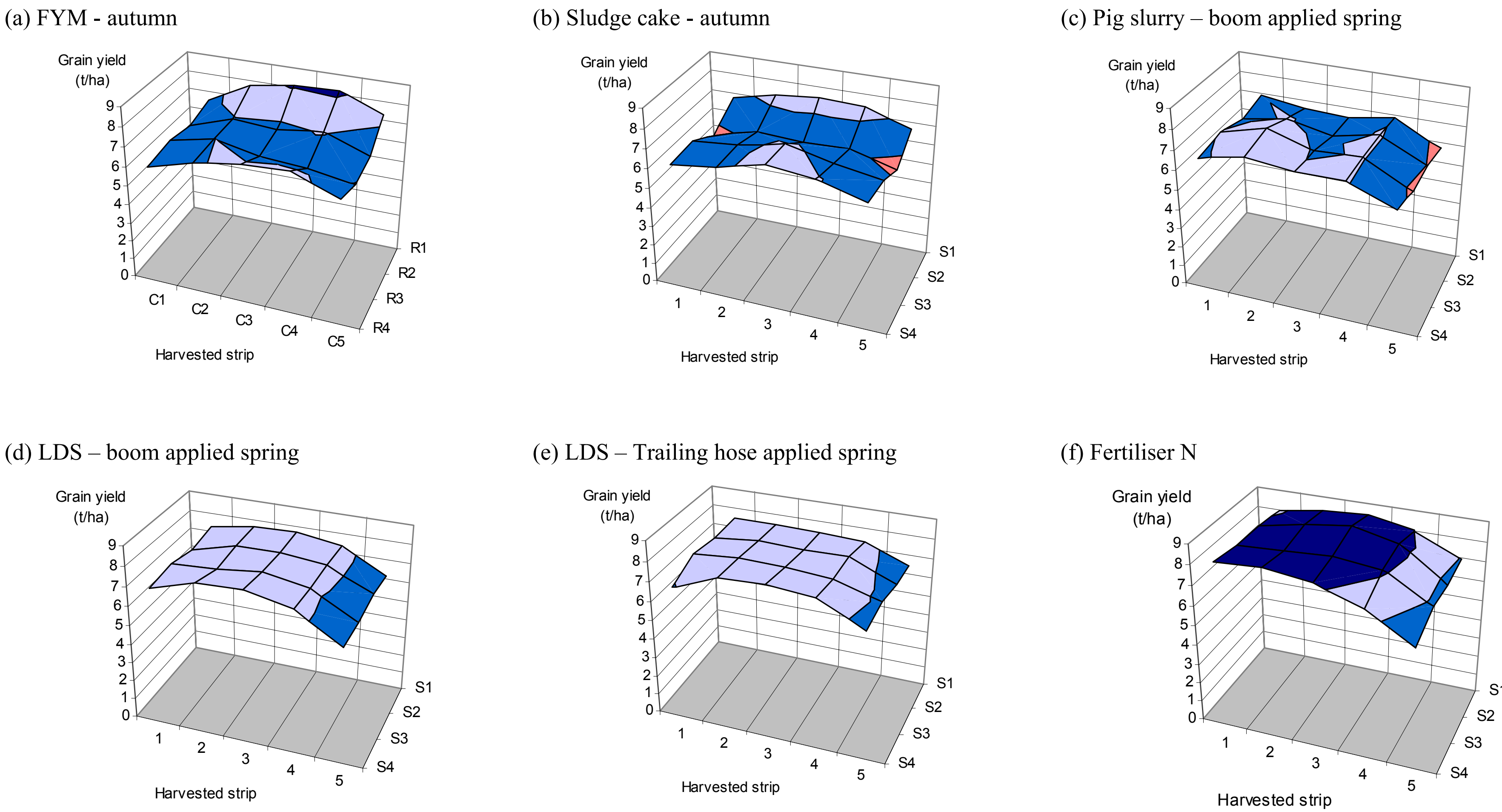


Figure 26. Surface plots showing yield variation across large demonstration plots at the Hattons site, 2000; yield assessments across small sub-plots by plot combine.

Table 39. Manure and fertiliser N treatments applied to demonstration plots at Hornby Castle, Bedale, 2000; with estimated plot yields harvested by GPS equipped combine.

Treatment	Application date	Manure application Application rate	Total N applied as manure kg/ha	a Estimated manure N available[1] kg/ha	b Fertiliser N GS 24 + GS30[2] kg/ha	Grain yield t/ha	(sed) CV%[3]
FYM, autumn	Sept.'99	60 t/ha	400	50	140	9.4	(0.13) 10.5%
Sludge cake, autumn	Sept.'99	30 t/ha	180	25	165	10.3	(0.05) 3.5%
Pig slurry, spring, surface broadcast (Boom & splashplate)	Mar. '00	25 m^3/ha	130	50	140	9.9	(0.09) 6.0%
Liquid sludge, spring, surface broadcast (Boom & splashplate)[4]	Mar. '00	50 m^3/ha	100	50	140	9.2[4]	(0.07) 4.8%
Liquid sludge, spring, surface broadcast (Boom & splashplate)	Mar. '00	75 m^3/ha	150	75	115	9.9	(0.07) 5.1%
Fertiliser N[5]	March & May '00	-	-	-	190	10.0	(0.06) 3.9%

[1] Estimated making allowance for losses due to N leaching, ammonia emissions, using MANNER.
[2] Fertiliser application at GS 30 (col. b) adjusted to give N equivalent to standard recommended = cols. a + b (190 kg/ha).
[3] Statistical data from GPS combine harvest assessments of plots.
[4] Yield depression across this plot attributed to the entry of cattle and resulting grazing and treading damage.
[5] Fertiliser N application according to standard recommendations (RB209).

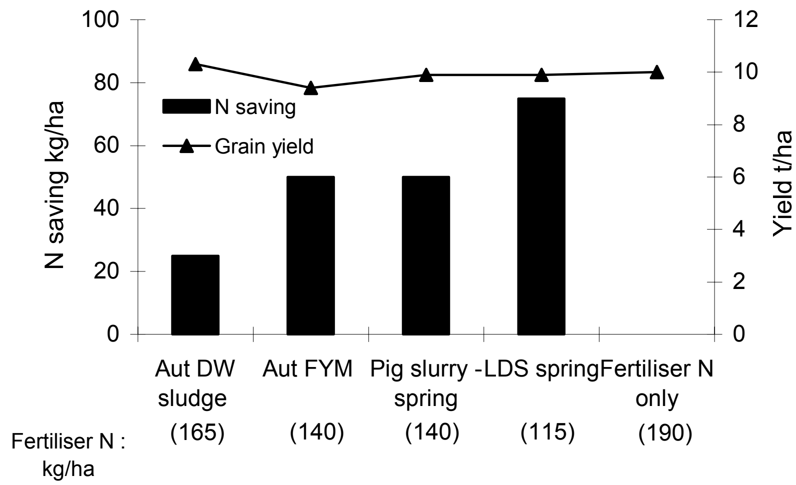


Figure 27. Organic manure treatments and crop response (winter wheat) to fertiliser and manure N, Bedale 2000.

6. DISCUSSION

6.1. Manure analysis and variability

Variability in manure analysis is often cited as a reason why farmers lack confidence in reducing fertiliser inputs after manure applications. Our data confirm that nutrient contents can vary within a manure type. Tables 40-41 show the mean value and also the standard error around that mean, which provides an indication of variability. However, the mean values are fairly similar to the standard values published in the industry standard reference book, RB209 (Anon., 2000). An example of the variation behind such data can be seen in cattle slurry N content (Fig. 28) (K Smith, unpublished data), in which the range about the 'standard' N content of 0.3% (i.e. 3 kg/m^3) at 6% DM is highlighted by the vertical arrow (*c.* 0.1-0.7% N). In this case, although there is a strong correlation between dry matter and total N content, there is also large variation in N content at a single level of dry matter. Another example of variability is shown in data supplied from Yorkshire Water (J. Brigg, Pers. Comm.), detailing variability in N and P content from a single works (Figs 29-30), presumably depending on fluctuations in inputs to the treatment works, and also weather (e.g. rainfall). Clearly, this variability has potential to cause problems in nutrient management at the farm level, but there are several approaches that can be used to manage this variability.

Table 40. Average nutrient content of each solid manure/sludge and comparison with 'standard values' taken as the industry norm and published in Anon. (2000). SE = standard error.

	DM (%)	Total N (kg/t)	P_2O_5 (kg/t)	K_2O (kg/t)	MgO (kg/t)	NH_4-N (kg/t)	NO_3-N (kg/t)
RB209	25	7.5	9.0	trace	1.3		
YW1	28.2	7.1	8.4	1.0	1.1	0.4	0.1
SE	1.06	0.67	0.73	0.09	0.08	0.19	0.08
YW2	23.7	8.3	7.3	0.6	1.6	1.2	0.0
SE	0.99	0.49	0.45	0.05	0.12	0.21	0.01
YW3	35.9	10.1	11.3	1.1	2.4	0.2	0.5
SE	2.28	0.89	0.70	0.11	0.25	0.11	0.17
ST1	21.8	10.1	9.3	0.4	2.0	2.2	0.0
SE	1.16	0.31	0.25	0.03	0.04	0.28	0.00
ST2	27.9	9.8	13.2	0.6	2.3	1.8	0.0
SE	1.17	0.31	0.75	0.04	0.07	0.12	0.00
RB209	25	6.0	3.5	8.0	0.7	0.6-1.5*	
FYM	40.0	5.9	3.5	10.7	3.4	0.1	0.3
SE	4.17	0.24	0.39	1.37	0.78	0.04	0.14

* Depending on age & management.

Whereas variability in N might be perceived as a large risk given a crop's typically large response to N inputs, there is much less risk associated with P and K input. Despite this, fertiliser use statistics show that farmers underestimate the P and K value of the manures (Smith & Chambers, 1995; Chalmers *et al*., 1998). However, most arable soils are adequately supplied with P and K (Skinner & Todd, 1998), such that only maintenance applications of phosphate and potash are required. At adequate levels of soil P and K, responses to fresh additions are unlikely (Arnold & Shepherd, 1989). Furthermore, soil P and K status change only slowly even if the soil is under- or over-fertilised (discussed in more detail later), so that using standard manure nutrient values (in the absence of manure analysis) is likely to be satisfactory. Combining this with periodic soil analysis (e.g. every 5 years) for standard nutrient content provides a further safety net. Management of risk is also discussed in more detail later. However, it can be seen that there is rarely a justification for not decreasing PK fertiliser inputs (often substantially) after manure/sludge applications.

Table 41. Average nutrient content of each liquid manure/sludge and comparison with 'standard values' taken as the industry norm and published in Anon. (2000). SE = standard error.

	DM (%)	Total N kg/m^3	P_2O_5 kg/m^3	K_2O kg/m^3	NH_4-N kg/m^3
Cattle slurry	6.3	3.2	1.3	3.3	1.6
SE	0.25	0.10	0.04	0.19	0.07
RB209	6.0	3.0	1.2	3.5	1.5
Pig slurry	3.7	4.2	2.1	3.7	2.7
SE	0.29	0.24	0.11	0.17	0.12
RB209	4.0	4.0	2.0	2.5	2.4
Liquid DS1	3.8	2.7	2.1	0.31	0.9
SE	0.11	0.10	0.15	0.04	0.04
Liquid DS2	2.4	1.8	0.7	0.26	0.85
SE	0.18	0.07	0.07	0.03	0.02
RB209	4.0	2.0	1.5	trace	1.0

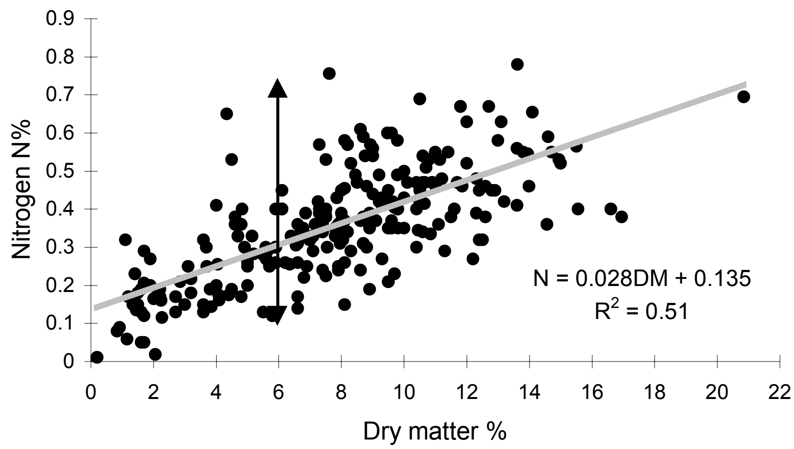


Figure 28. Variation in cattle slurry N content with dry matter content; 'standard' N content given at 0.3% for 6% DM slurry (Anon, 2000) but the range in N content is shown by vertical arrow.

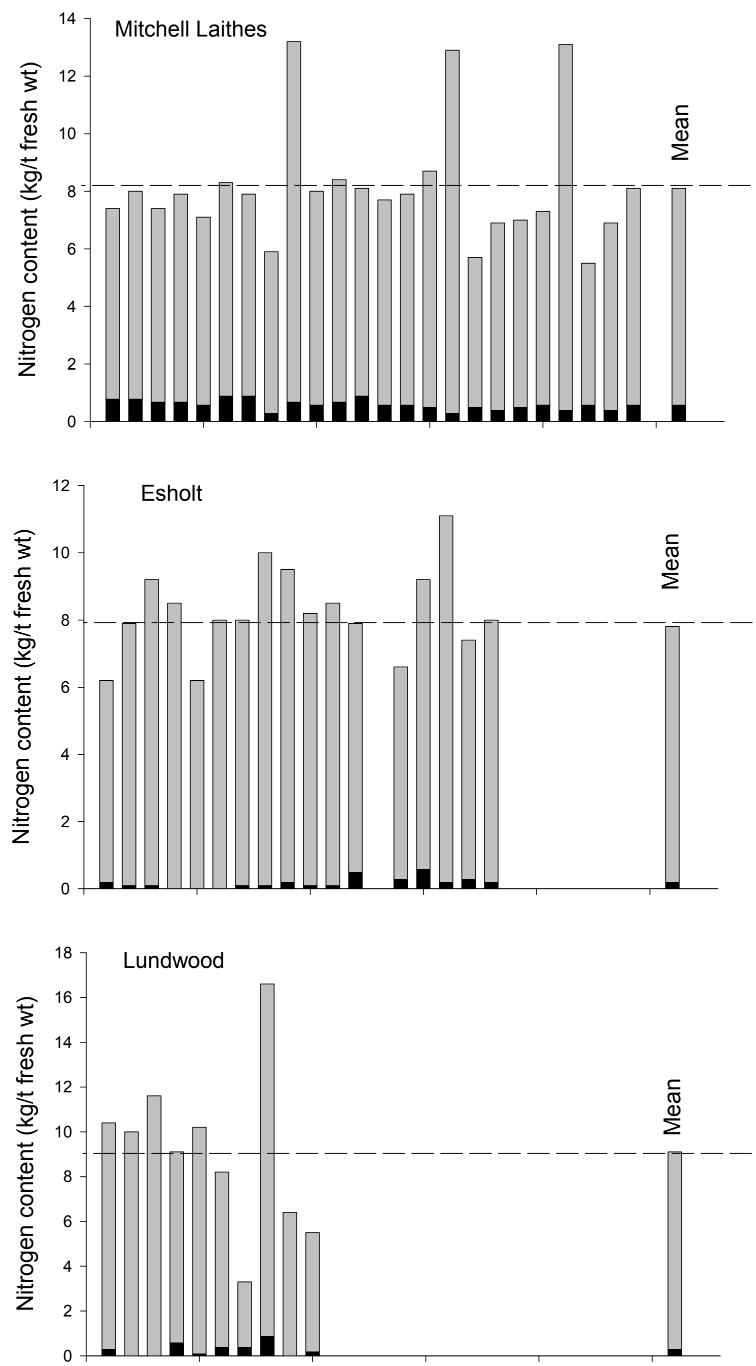


Figure 29. Variation in the N content of sludge samples taken from three works during 2000. Black bars denote NH_4-N content, grey bars denote total N content.

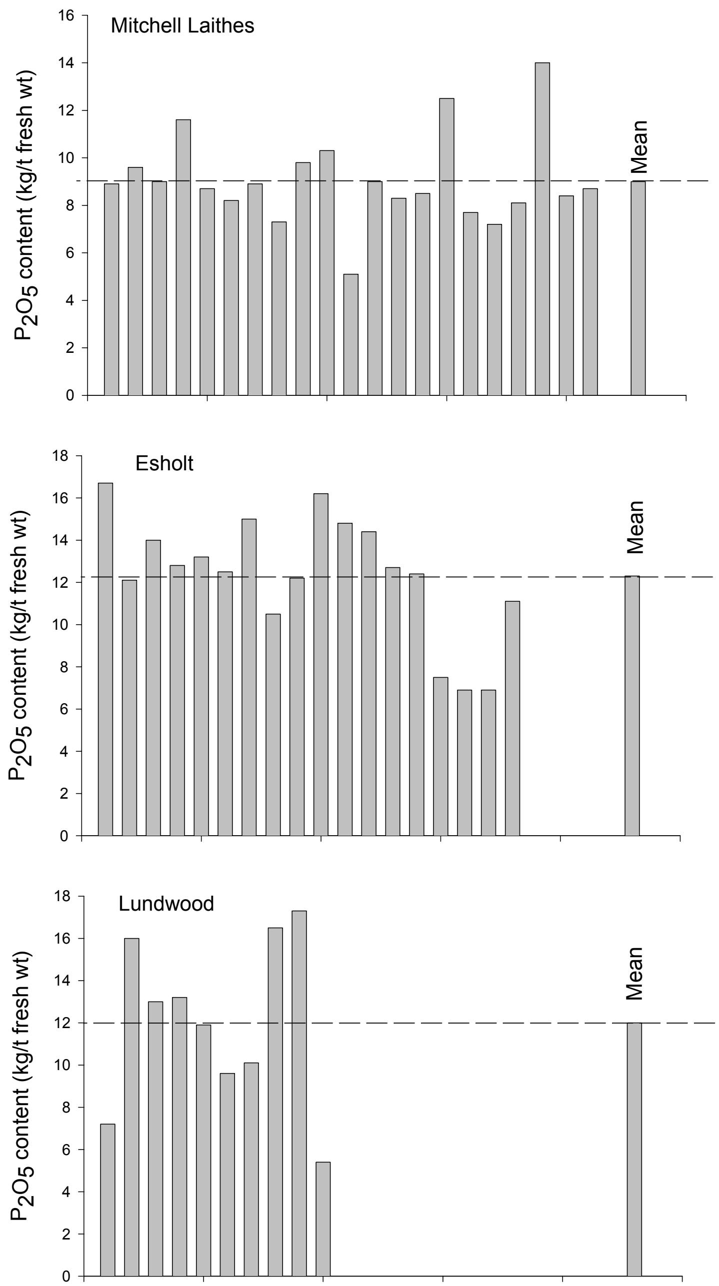


Figure 30. Variation in sludge phosphate in samples taken at fortnightly intervals from three works (Yorkshire Water).

Because of the extent of crop response to under- or over-supply, N is seen as the high-risk nutrient and the main issue for risk management, which is analysed in more detail later. Whereas analysis of soil Nmin is of some value for determining soil supply after manure/sludge applications (Shepherd, 1993), cost and operational constraints preclude this from becoming a routine analysis. Therefore, other strategies have to be considered:

- Use of standard nutrient values – work by Shepherd (2001) showed that, in the medium-term, the use of standard nutrient values for manures (e.g. those published in RB209), provides a good estimate of nutrient inputs. This is perhaps not surprising, since the standard values are calculated from a large number of individual analyses. However, whereas this standard value approach is satisfactory for P and K (as discussed above), it is less useful for N given the crop's likely responsiveness to this nutrient.

- Laboratory analysis of manure – disadvantages of laboratory analysis include cost, delay in obtaining the result and the difficulty in obtaining a representative sample of the manure in the first place. Sampling protocols are available, which aim to achieve a representative sample (Chambers *et al*., 2001), but the time and effort should not be underestimated. However, it could be argued that occasional laboratory analysis is worthwhile for an individual farm unit or sludge works, where production methods are consistent. Here, periodic analysis is likely to give a better assessment of manure or sludge nutrient content, with most of the variation from the average nutrient content explained by addition or exclusion of water and, hence, dilution or otherwise of slurry or sludge, or moisture content of solid manures/dewatered cakes.

  Water Companies may have an advantage here because they all provide analysis of sludge products on a routine basis. However, this is not always down to the level of an individual load (I. Fairless, Pers. Comm).

- On-farm analysis – methods have been available for some time for liquid manures, and it is perhaps these manures, with a high proportion of readily available N, where the test is of most value. Tunney (1986) showed a relationship between N and dry matter content, and also P and dry matter content. Shepherd *et al*. (2002a) found similar dry matter relationships with manures from organic holdings. Relationships were poorer for K since most of this is found in the urine rather than being associated with the solid matter. Also, it was found that the relationship with the ammonium fraction of the manure was poor – again, because most is derived from the urine phase.

  However, other methods are available for ammonium N determination of liquid manures: the Agros and Quantifix meters. These were used and demonstrated in this project. They both work on the same principle of oxidising NH_4-N to dinitrogen gas in an enclosed chamber. The pressure is correlated to ammonium N content, as demonstrated by Bhogal *et al*. (2001), Figure 31. It can be seen that an occasional laboratory analysis can be supplemented by more regular checks using a portable slurry N meter or hydrometer, thereby providing a reliable and accurate strategy for gauging slurry N applications at the farm level. Moreover, in recent research, these techniques were tested by a group of 16 farmers, with similarly good results (Williams *et al.,* 1999). Over half the farmers in the latter study indicated that they would be prepared to buy an N meter or conductivity meter, although they indicated that they would not be prepared to pay more than £200 (UK) for the equipment (i.e. covering the cost of a hydrometer but short of the cost of the N meters). The majority also indicated that they would reduce their inorganic fertiliser N applications on the basis of results obtained with the on-farm analysis techniques.

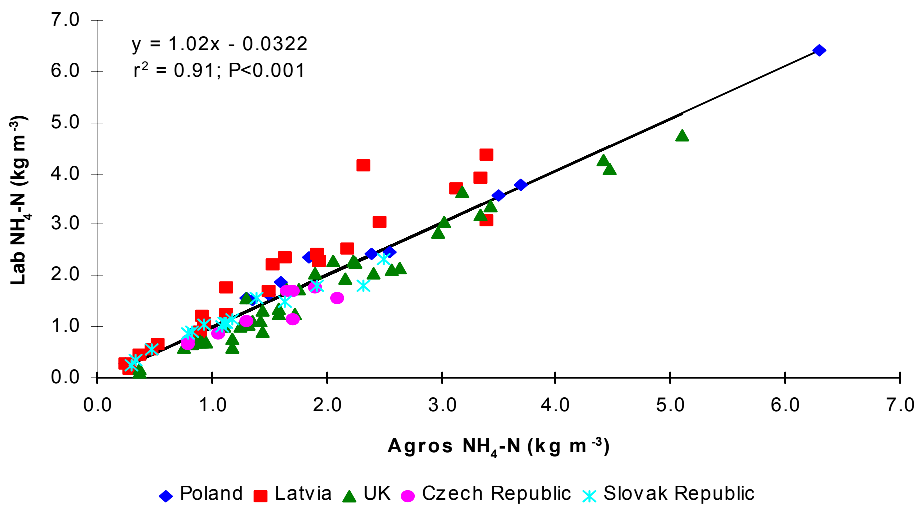


Figure 31. Relationship between laboratory NH_4-N analyses and Agros meter readings (from Bhogal et al., 2001).

These methods do not work for solid manures. This is unfortunate for poultry manures, which have a large available N content, but less so for the FYM, dewatered cakes and composted cakes used in this project because they generally have small NH_4-N contents. However, Lorimer *et al*. (1999) and Reeves & van Kessel (1999) have shown that techniques based on near infrared reflectance spectroscopy (NIRS), offer potential for the analysis of solid manures, particularly for nitrogen and carbon containing compounds. This potential has been confirmed by Farrington *et al*. (2000) in the UK and work is underway to develop a rapid, low-cost analysis service for solid manures.

The project also showed that, in some circumstances, nitrate can contribute to the fertiliser value of these solid manures. The presence of nitrate is associated with aerobic conditions (usually composting), and not normally with farm manures managed and stored in conventional ways. Consequently, it has not been a part of the routine suite of analyses, given that only trace amounts have been detected in the past. But nitrate can be found in composted manures (Dewes & Hunsche, 1998; Shepherd *et al*., 2002a). There was evidence in the old, composted FYM used in this project and the composted sludge cakes that nitrate can be a significant proportion of the readily available N fraction. Its analysis therefore needs to be included as a routine.

6.2. Nitrogen partitioning between soil and crop, nitrogen balances

The upper application rate of 750 kg/ha N for the solid manures was above any rate recommended in existing Codes of Practice, but it was included to allow tracking of the applied N over three years. Table 42 shows the partitioning between N removed from the field in harvested crop and that leached from the soil over three winters.

The same calculation was possible for two other application rates: 500 kg/ha N and the three annual applications of 250 kg/ha N. Figure 32 shows the partitioning as an average of these three rates. Statistical analysis showed that application rate had no significant effect on the proportion of the applied N that was allocated to each pathway. Nor was there any significant site effect (P>0.05).

Table 42. Nitrogen balance constructed for solid manure/sludge applications Gleadthorpe (Gt) and Emley (Em), for the target application rate of 750 kg/ha N.

	N applied (kg/ha)		Crop N removal (kg/ha)		NO_3-N leached (kg/ha)		Balance (kg/ha)	
	Gt	**Em**	**Gt**	**Em**	**Gt**	**Em**	**Gt**	**Em**
Control	0	0	64	201	138	133	-202	-334
Se			5.6	6.0	4.5	2.7	6.6	6.6
YW1	722	687	104	227	180	142	438	317
Se			10.9	7.8	7.5	20.4	18.1	22.8
YW2	780	762	202	285	232	245	347	232
Se			18.5	11.0	13.5	18.8	13.0	29.8
YW3	662	791	146	225	231	256	285	311
Se			21.1	15.3	10.1	24.9	31.1	9.7
ST1	703	710	178	300	209	239	316	171
Se			6.2	7.1	39.5	4.5	42.0	3.1
ST2	756	769	128	285	181	223	447	262
Se			8.0	1.9	19.0	13.2	25.4	15.1
FYM	806	663	115	248	195	202	496	213
Se			6.9	16.2	20.1	6.8	25.2	9.8

Allowing for the background ‘control’ contribution to crop N removal and N leaching, the calculations show that 75-90% of the applied N remains in the soil after three years. This has important implications for soil fertility. There was, however, a significant manure type effect, which could be explained by understanding the manure characteristics. Largest removals were from the two ‘fresh’ sludge cakes (YW2 and ST1) because these had a larger proportion of readily available N (i.e. ammonium-N), which could be leached and/or used by the crop. The composted manures, with most of the N bound in recalcitrant forms, contributed most to the soil organic N pool. Although the composted dewatered cake YW3 would have provided a large recalcitrant organic matter pool, it also contained substantial nitrate that was leached.

These results have important implications for soil quality. Increasing organic matter levels are associated with improving soil structure. In fact, many farmers, especially on light soils, value the organic matter from manures as much as the nutrients (M. Shepherd, Pers. Comm). Both the fresh, easily degradable organic matter and the more stable humic fraction of manures contribute to soil structure improvement (Tisdall & Oades, 1982). However, it is particularly the easily degradable organic fraction that improves aggregate stability, by encouraging microbial activity during breakdown (Shepherd *et al*., 2002b). Further work is required on the potential benefits of composted materials, because much of the readily decomposable organic matter would have undergone degradation in the compost heap before application to the soil.

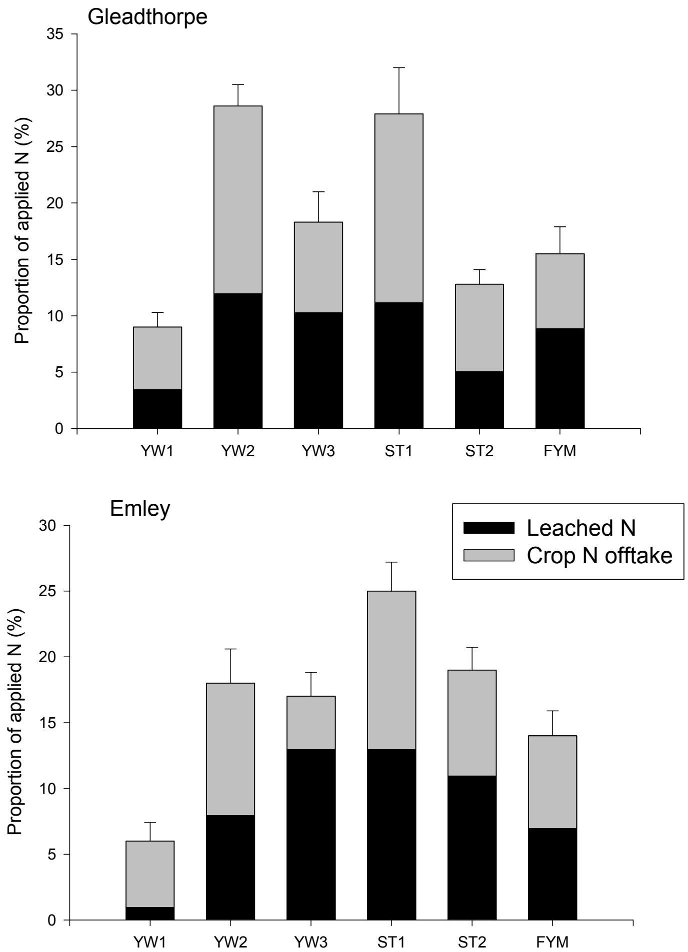


Figure 32. Proportion of N removed by leaching and crop off-take (% of N applied in FYM/sludge cakes) as a total of three years for the Gt and Em sites.

6.3. Fertiliser Replacement Value (FRV)

FRV depends principally on the following elements:

Crop N supply	=	NH_4-N content	–	N volatilised	–	N leached	+	organic N mineralised

The NH_4-N content represents the 'readily available N' fraction. For poultry manures, it also includes the uric acid fraction, which is rapidly converted to ammonium (Groet Koerkamp & Elzing, 1996). Previous workers have considered the uric acid fraction as being organic (strictly true), but its conversion to ammonium is sufficiently rapid to warrant its inclusion in the readily available fraction. Adopting this approach, as in the MANNER model, showed good agreement between measured and calculated fertiliser N supply. This project has shown that, for some manures, nitrate can form a considerable proportion of the readily available N and this needs also to be included where it is relevant.

The above scheme explains the rationale of the project. For liquid manures, with a large readily available N component, the aim is to minimise losses by leaching and volatilisation. For solid manures (excluding poultry), the emphasis had to be on understanding mineralisation of the organic fraction and optimising application timing.

The above framework also demonstrates that all of the above factors need to be understood and quantified in order to develop a reliable recommendation system.

6.3.1 Factors affecting FRV

For solid manures, statistical analysis showed that the following factors affected the FRV: year and manure type. There was also a year x type interaction. Rate had no effect on the FRV, expressed as a proportion of the N applied (but, obviously would have an effect in terms of absolute amounts).

For the solid manures, we did not examine time or application, or speed and method of incorporation. Given the available resources within the project, the aim was to focus on autumn applications and on the organic fraction. Indeed, because these materials are not appropriate for top-dressing the growing crop (other than grass), then the most often used strategy for solid manures is ploughing down in the autumn (Smith *et al.,* 2000). However, using the MANNER model, adjusted for more appropriate mineralisation factors for each manure type (see later), it was possible to examine the effects of decreasing nitrate leaching and ammonia losses on the total FRV. Table 43 shows that for composted manures with a low ammonium-N content, there was little benefit of adopting techniques that reduced losses (e.g. YW3, FYM and, to a lesser extent, YW1). The greatest benefits were with the fresh manures with a larger ammonium content, as would be expected. Then, there was clearly an advantage in decreasing losses. Note that this calculation did not include consideration of nitrate. If the composted manures contained significant nitrate, then delaying application of the manure needed to be considered, to decrease leaching of this component.

Table 43. Calculated effects on FRV (% of applied N) of stopping nitrate leaching by applying in spring and by reducing ammonia volatilisation and nitrate leaching by applying in spring and quickly incorporating. Assumed complete reduction of leaching and halving volatilisation losses by ploughing down within 24 hours. Calculations assume no nitrate content in the manures.

Manure	Autumn application, surface	Spring application, surface	Spring application, quick incorporation
YW1	5	9	12
YW2	12	20	26
YW3	5	7	8
ST1	13	18	21
ST2	4	12	18
FYM	5	6	6

For liquid manures, only a limited range of factors likely to affect FRV could be studied within the project. As anticipated, application time had a major impact on FRV, with the highest manure N efficiency (for all manure types) consistently recorded following applications at GS 24 and GS30 (P<0.001). Though not studied in this work, the importance of the solids content of slurries has been clearly demonstrated before (Smith & Chambers, 1992), with %FRV increasing with decreasing solids content. The liquid manures were applied, throughout, using the trailing hose, surface banding application technique, which has been shown to significantly reduce ammonia emissions in the past (Smith *et al*., 2000). Such ammonia emission abatement measures, when used under favourable conditions, would be expected to increase the efficiency of slurry N utilisation, though these effects were not specifically studied within the project. Webb *et al*. (2001) used MANNER to evaluate the impact of ammonia abatement measures on the potential for nitrate leaching following manure applications. These studies concluded that, in order to avoid any conserved, readily available nitrogen (RAN) being subsequently lost by nitrate leaching, abatement techniques should not be used (e.g., for pig slurry) before the end of October, on any soil type. Moreover, delaying low emission slurry applications until early December would improve crop utilisation of the conserved N, except on sandy soils in high rainfall areas. More generally, it was suggested that slurries could be applied (and incorporated) from early January onwards, without causing additional nitrate loss. Recent results from Shepherd & Harrison (2000) concur with this view.

6.3.2 Mineralisation impact for nutrient supply

The organic N fraction of manures has been considered as comprising several pools, relating to the ease of breakdown (Jarvis *et al*., 1996). Some authors consider urea and uric acid as organic compounds (Beauchamp, 1986) whereas, in practice, these compounds are quickly converted to ammonium.

The ‘true’ organic fraction is often considered as following a curvilinear or two straight-line degradation, being driven by temperature (thermal time): Jarvis *et al*. (1996). This corresponds to a rapid degradation of the easily decomposable fraction followed by a more gradual mineralisation of the more recalcitrant fraction. This classic pattern can be seen for the dewatered cakes YW2 and ST1 during the aerobic incubations (Figs 22 and 24). However, this same pattern was not noted for the composted materials, particularly YW1, YW3 and FYM. It could be argued that this is because the readily degradable component has been broken down during composting, leaving only a more recalcitrant fraction for degradation on application to the soil.

The incubation studies were therefore a useful indicator of the likely performance of the materials on application to the soil. On the basis of the limited number of observations within this project, NIRS was not a good predictor of mineralisation potential. However, other research suggests that this warrants further investigation. NIRS was a good method for predicting total N and DM contents. It has the advantage of analysing a larger sample than is used for wet chemistry (Farrington *et al*., 2000), and so is likely to be more representative. It is also quicker than wet chemistry. Further effort should therefore be devoted to developing a sufficiently large dataset to correlate analytical values with NIRS.

6.3.3 Prediction: MANNER and other recommendation system comparisons

The UK standard fertiliser recommendation systems for manure nutrient value are RB209 (Anon., 2000) and MANNER (Chambers *et al*., 1999). MANNER currently deals only with N, though a new version is being developed to account for other nutrients. Manure fertiliser N values in the look-up tables in the current (7^{th} edition) version of RB209 have been generated from MANNER. Thus, the best test for our data is to compare with MANNER.

Numerous field experiments were compared with MANNER during its verification (Chambers *et al*., 1999), and agreement between measured and modelled was shown to be good (less good for autumn-applied poultry manure). It is accepted that, to date, a weakness has been in the N mineralisation component of the model, taken as 10% of the organic fraction being crop available and derived from relatively few empirically based field observations (B. Chambers, Pers. Comm). Whereas, this has proved satisfactory as a first approximation (e.g. Shepherd & Bhogal, 1998), a Defra-funded research programme has just been completed to improve this aspect (NT2106). Data from this SAPPIO project provides information on dewatered sludge cakes and composted materials that were not included in the Defra-funded project.

The aims of the SAPPIO project included a focus on organic N release from the organic component of the manures. However, because these materials inevitably also contained ammonium N, this also needed to be taken into account if we were to be able to estimate the mineralisation component of the organic fraction. Two approaches were therefore adopted to estimate mineralisation of the organic component:

- First, the MANNER algorithms were assembled on an Excel spreadsheet, allowing adjustment of the mineralisation factor from 10% of the organic component being available. It was assumed that the leaching and volatilisation components were valid, and the organic component was adjusted to provide best fit to the data.
- Secondly, the revised mineralisation algorithms from the Defra-funded project (Bhogal, 2002) were compared with our estimates of mineralisation from this project.

Figure 33 shows the results of adjusting the mineralisation component, by plotting the measured FRV against modelled FRV. Figure 33a shows that there was generally poor agreement between predicted and measured N release rates using the original MANNER model. This was not surprising, given that our results included composted manures that were not considered in the original MANNER model.

The first adjustment (Fig. 33b) shows the effects of allocating a mineralisation factor of 15% to fresh dewatered cakes (YW2, ST1, ST2) and 5% to composted materials (YW1, YW3, FYM). These numbers were based on sound logic. RB209 (6th edition) applies a factor of 15% (Anon., 1996). The composting process will have broken down much of the labile N, as discussed above, and a 5% rule of thumb seems logical. This fitted the data. However, the enigma throughout the project has been the ST2 dewatered cake, which was originally considered a dewatered cake, but behaved more like a composted cake. This is in line with the reported 'difficulties' during the processing of the particular batch of cake that was used in this experiment (C. Rowlands, Pers. Comm). The field experiments and the first-year incubation studies, showed it to be a low mineraliser than would be expected from its allocation simply as a 'dewatered cake', and it behaved similarly to the composted materials (e.g. Fig. 22). When it was allocated a smaller mineralisation component (5%), based on the evidence of the laboratory tests, then the fit between predicted and measured FRV was good (second adjustment, Fig. 33c), with a non-significant intercept and a slope of close to unity.

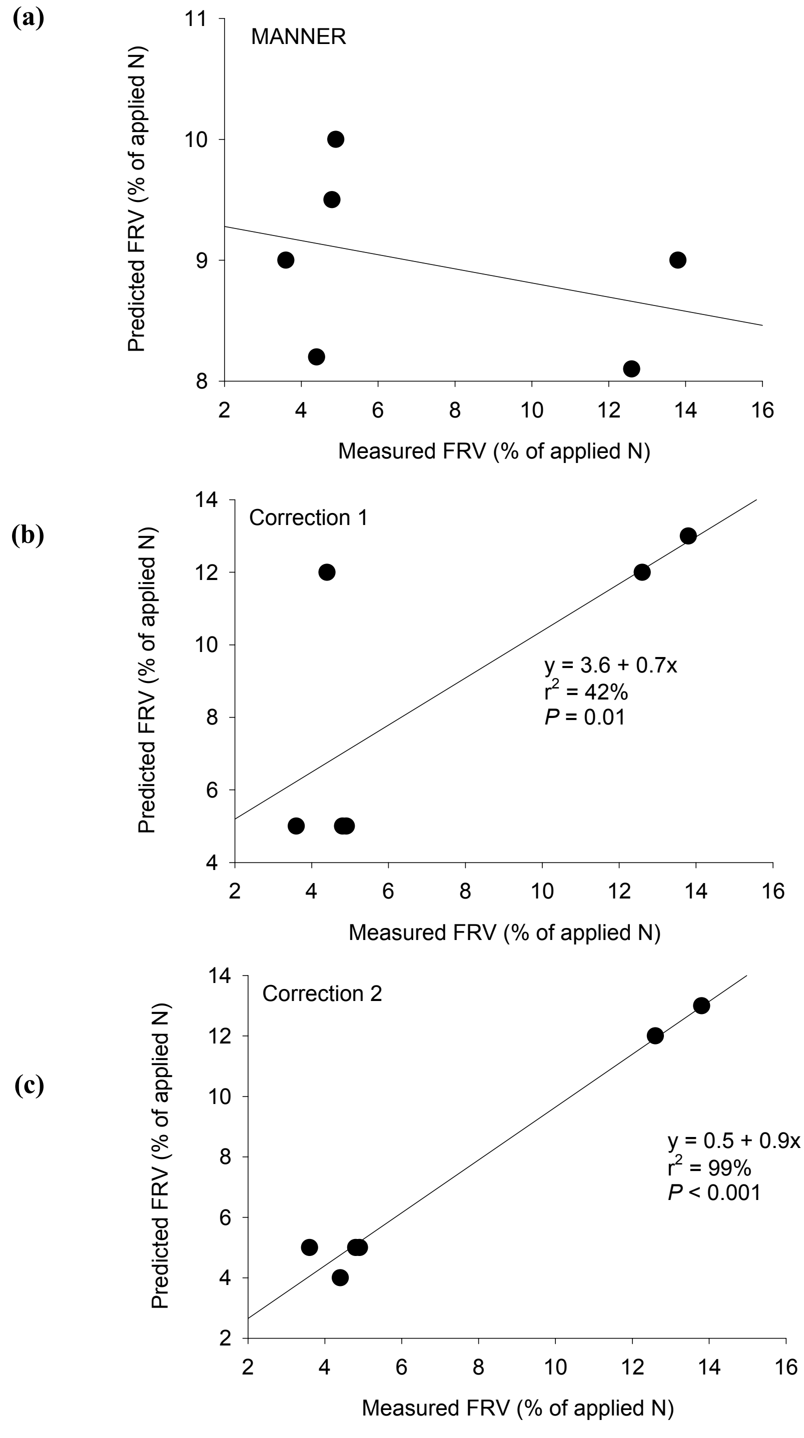


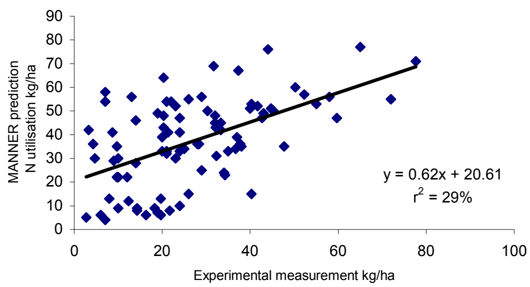
Figure 33. Comparison of measured and predicted fertiliser replacement value (FRV) at Gt.

Thus, we have evidence from the project that two mineralisation factors should be applied to the materials used in the project: 15% for fresh dewatered cakes and 5% for composted cakes and manures). We have been unable to compare measured FRVs in the second and third years against recommendations because, currently, recommendation systems do not take account of residual effects, although Anon. (2000) suggested that digested cake would supply N equivalent to 10% of applied in the second year and 5% in the third year. However, there is a current Defra-funded project that is developing a longer-term soil N accounting model (SNSCAL, E. Lord, Pers. Comm), where the data will be used.

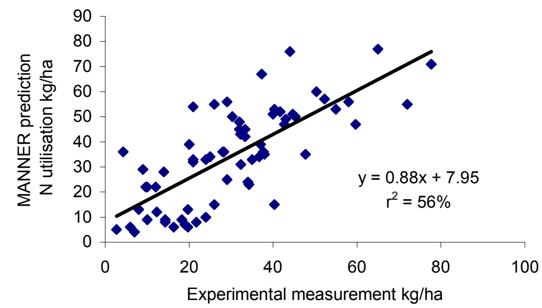
The second approach to estimating mineralisation factors for the manures used in this project was to compare the data with the newly developed mineralisation algorithms from the Defra-funded project NT2106 (Bhogal, 2002). This separated manures in to 'slow' and 'rapid' mineralisers based on manure type. However, the project did not include composts, nor dewatered cakes. It was assumed that dewatered cake would be a slow mineraliser because it had already undergone some digestion during processing. The algorithms were driven by accumulated day degrees (CDD) above 5 ^{o}C. The Bhogal algorithm was used for fresh FYM and CDD from mid-November 1998 (time of manure application) to mid-July 1999 (assumed to be when the growing cereal crop would take up minimal N from the sludge). The estimated organic N release factor was 16% of the total N, which showed excellent agreement with our independent estimate of 15%.

For the liquid manures, the results summarised in Figures 15 and 16 follow the expected pattern, with the measured %FRV reflecting the analyses of the manures (Table 23) and the time of application. Pig slurry which had the highest proportion of RAN, with NH_4-N/N at 66% and a low solids content of 3.7%, compared with NH_4-N/N at 50%, 34% and 48% for the cattle slurry and the two liquid digested sludges, respectively.

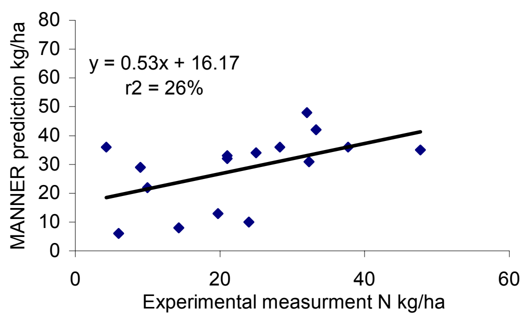
Figure 34 shows the results of the MANNER predicted FRV for the liquid manures compared with experimentally measured values. Where the results over the 3 years for all manures, across all application timings are compared with MANNER predictions, the correlation was poor (Fig. 34a). This was not surprising since FRV of the later (GS39) applications was relatively low, the manure N applied at this time being known from earlier research to be associated with lower efficiency and also some risk of foliar scorch (Smith & Chambers, 1992). However, MANNER is not currently equipped to deal with such scenarios. Where comparisons of the MANNER predictions were restricted to autumn, and the earlier spring timings, the correlation with field measurements was encouraging (Fig. 34b, 34d, 34e), giving further confidence in the use of MANNER to provide guidance on manure N replacement values. Only in the case of cattle slurry (Fig. 34c) was the prediction less consistent, but this result can be attributed to the variability obtained in 2 or 3 observations and to the relatively narrower range of manure N application rates achieved within these studies.



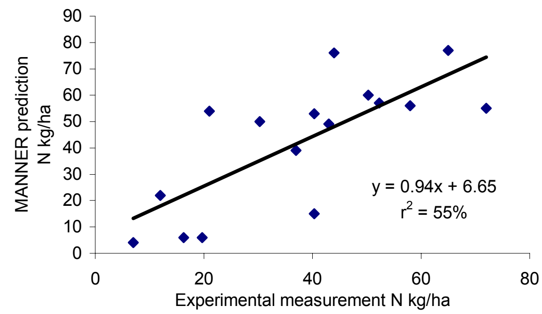
(a) All manures, applications aut, GS24, 30, 39



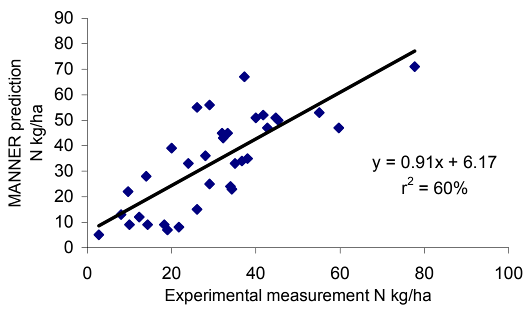
(b) All manures, excluding applications GS39



(c) Cattle slurry, excluding applications GS39



(d) Pig slurry, excluding applications GS39



(e) Liquid sludges, excluding applications GS39

Figure 34. Comparison of experimentally measured liquid manure N fertiliser replacement value (FRV) and MANNER predicted FRV.

6.4. Environmental Issues

6.4.1 N losses

The results confirm some differences in leaching risk between materials (i.e. between the liquid and solid manures tested), although the data were not as conclusive as shown by other work. For example, Beckwith *et al.* (1998) and Chambers *et al.* (2000) clearly showed a larger leaching loss from poultry manures and slurries (i.e. materials with a large proportion of readily available N) compared with FYM. Similarly, Shepherd (1996) showed a difference between liquid digested sludges and dewatered cakes. Results such as these underpin the requirements of the EC Nitrates Directive to have closed windows of manure/sludge applications in autumn/early winter on sandy/shallow soils. Beckwith *et al.* (1998) concluded that December was satisfactory for slurry applications on sandy soils, i.e. subsequent leaching losses were acceptably small.

Although subsequent leaching losses are driven by the amount of rain after application, rather than calendar date, nitrate losses were surprisingly small at the Hattons site following slurry and liquid digested sludge applications in mid-November. However, applications were left on the surface, which would have had two effects: first, some N would be lost as ammonia, thus decreasing the amount available for leaching. Secondly, the nitrate would have further to travel before being lost from the rooting zone (compared, for example, with burial at depth by ploughing). Such conflicts in emissions via different N flux pathways are becoming more of an issue, because it is not acceptable to decrease N losses to the environment via one route, while increasing them by another (so called 'pollution swapping').

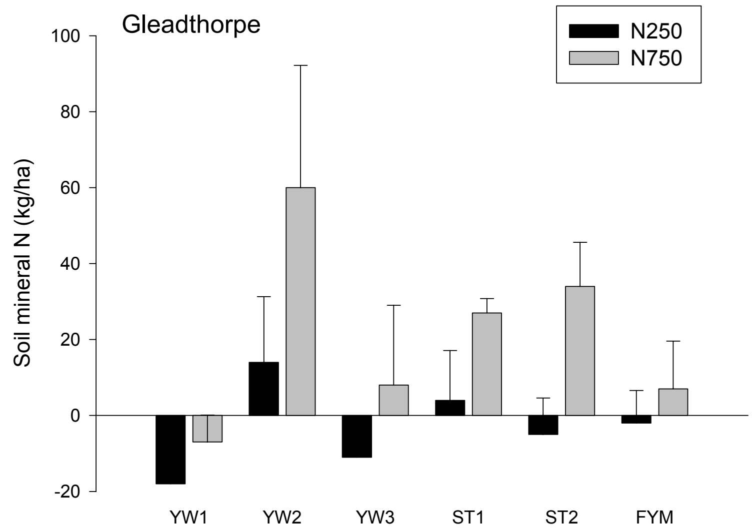
Our data on nitrate losses from the dewatered cakes and FYM show several important points when considering nitrate policy:

- There is a small risk with manures containing a small proportion of readily available N, which confirms current policy. However, as discussed above, there is an issue with high nitrate contents in composted manures. We measured substantial nitrate losses from manures/composted sludges that contained nitrate. This is not currently accounted for but is a potential risk, if composting increases as a method of recycling materials to agricultural land.
- Application rate is important. Defra's Water Code (Anon., 1998) suggests that biennial applications of low available N manures at a nitrogen rate of 500 kg/ha are acceptable (except within NVZs). Our data would support this. The approach has advantages, not only to Water Companies in their sludge spreading but, also, for farmers with FYM, because the restriction to lower application rates, over a wider area, effectively increases the operational costs of spreading. However, limits within NVZs are smaller: an annual maximum of 250 kg/ha N on individual

fields, but limits averaged over the farm area of 210 kg/ha N for arable and 250 kg/ha N for grassland (including grazing returns). Our data suggest that the 500 kg/ha N rate would still be acceptable. A rate of 750 kg/ha N was also included in the project, but we can conclude that this is too large to keep nitrate leaching losses from autumn applications within acceptable limits. It also has consequences for nitrate leaching in the following winter – see below.

- There was a large leaching effect from the dewatered cakes in the following winter after application (i.e. after the first harvest, Fig. 35) at the highest application rates. This was probably due to continued N release after the crop had started to senesce. Thus, the implications of policies in the following year also have to be considered.

Ammonia losses, following application of the liquid manures, were measured at the Hattons site (for GS 24 and GS30 applications only) using passive diffusion samplers, commonly known as dynamic chambers (Svensson, 1998). The measurements were too few and generally too variable to draw any firm conclusions, although it can be seen from Figures 21a-c that cumulative losses from sludges, for which there are few data, followed a pattern very similar those from other manure types and are well described by a Michaelis-Menten function. Losses from the liquid sludges tended to be lower than from the slurries, possibly as a result of their lower solids contents, though differences reached significance on one occasion only (P<0.05, GS30, 2000) (Table 29).



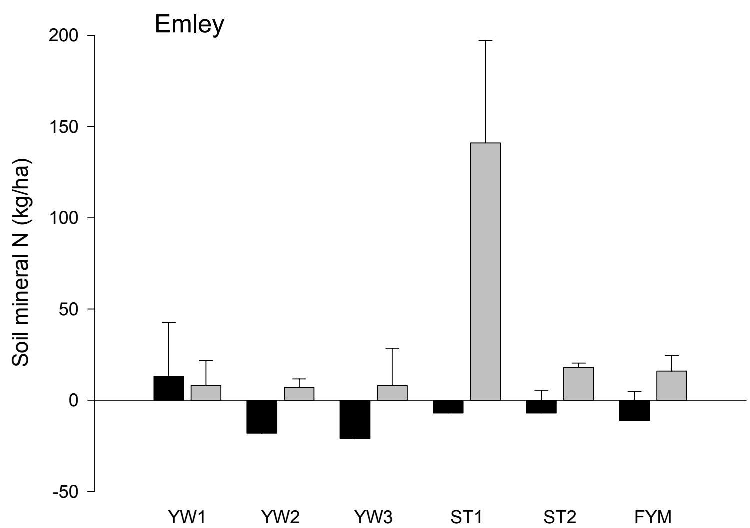


Figure 35. Post harvest soil mineral N at Gt (0-90 cm) and Em (0-60 cm), after harvest 1999, i.e. in the second autumn after application. Manure/sludges applied at two rates: 250 and 750 kg/ha N. Error bars denote standard errors.

6.4.2 Metals

It was not the aim of this project to examine in great detail the issues of heavy metal contamination from manures/sludges. This is because several other projects, funded by Defra and the Water Industry, are addressing these issues. However, our data contribute important information to the debate about metal loadings and sludge use. This is important, because it is often raised as an issue and, indeed, it was a major talking point at the Open days that we held as a part of the project.

Other projects are indicating that sludges are generally becoming cleaner in terms of metal loadings. Figure 36 shows an example of this for cadmium (Severn Trent Water data). This is because of greater regulatory controls placed on emissions from industry and, also, the general decline in heavy industry in the UK.

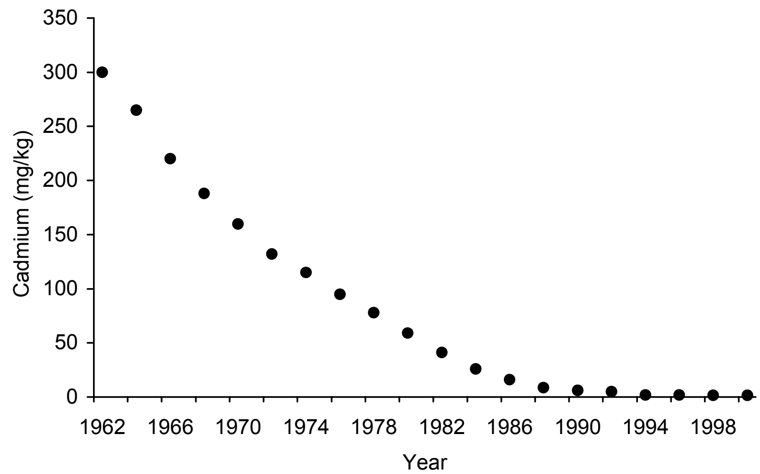


Figure 36. Decline in cadmium level in sludge from Severn Trent Water, Stoke Bardolph works, Nottinghamshire

However, data from this project show that some sources of sludge can have elevated levels of one or more metals, depending on the catchment for that sludge (e.g. ST2 sludge). The point is, though, that legislative controls are such that metal contents have to be monitored in the sludges themselves, as well as measuring soil accumulation from additions. This gives a very good safety net. For example, the ST2 sludge was not used on agricultural land because of its historical high zinc content. With the tight controls of today, most sludges are of suitable quality to go to agriculture.

Grain concentrations of all metals were well within safe limits following sludge applications, even though we were testing a 'worst case' situation: i.e. applications of sludge/manure in the absence of additional fertiliser N. In practice, fertiliser N would be applied in addition to the manure/sludge. The extra yield resulting from the fertiliser would dilute grain metal concentrations still further. Therefore, even though we did not use fertiliser practices that would dilute grain metal concentrations, we still did not see problems.

The resultant average metal loadings arising from the application of the slurries and liquid sludges at the Water Code 250 kg/ha N limit on annual additions, are summarised in Table 44, though without statistics on variability. In the experiments reported here, the target liquid manure application rates (supplying c. 120 kg/ha N) and, hence, metal loading rates were rather smaller than those shown in Table 44. Based on the analyses, it is possible to estimate how long such applications can be made to agricultural soils before the statutory limits for concentrations of PTE's in the soil are approached. Starting from the median levels of metals in topsoils in England and Wales (McGrath & Loveland, 1992), such calculations suggest that these manures might be applied annually for over 100 years. In each case, the first limiting element was zinc, with copper the next most limiting.

Metal applications from solid manures (Table 44) show higher loadings than from the liquid manures. The solid manures tended to have a higher metal concentration expressed on a fresh weight basis, which is not surprising given that these materials have a much higher dry matter content. Comparing concentrations on a dry matter basis showed that concentrations of metals were similar between liquid and solid sludges (Tables 11 and 25).

Table 44. Average metal loadings associated with slurry, liquid sludge, dewatered sludge and FYM applications supplying 250 kg/ha manure N.

	Loading (g/ha)					
	Zn	Cu	Ni	Pb	Cd	Cr
Liquid manures						
Cattle slurry	1575	509	25	25	1.6	44
Pig slurry	1911	1451	20	21	1.0	30
Liquid sludge LDS1	3319	2792	268	391	9.3	319
Liquid sludge LDS2	3480	947	159	474	6.5	680
Solid manures						
YW1	3678	1643	209	1975	5	681
YW2	8044	1822	315	1331	12	2129
YW3	5845	2404	345	1901	22	697
ST1	3540	2141	252	729	5	667
ST2	12693	2855	1053	4611	35	1305
FYM	1713	542	86	238	2	176

Metal concentrations in the animal manures were generally less than in the sludges, however. Pig slurry had high levels of zinc and copper. It is also worth noting that sludge applications are heavily regulated, which is not the case for animal manure metal loadings. However, within NVZs, manure N loadings are restricted to 250 kg/ha N, which will indirectly limit metal loadings. Animal manure applications (total tonnage) are also much larger than sludge loadings. Biosolids represent only 1-2% of organic N recycled, so that the total metal loading to agriculture is greater from animal manures than from sludges (Nicholson *et al*., 1998).

6.4.3 P effects

Analysis of the manures/sludges confirmed that they were valuable sources of P, and that the manures also contain substantial K. Current fertiliser advice is that once soils are well supplied with P and K, then maintenance dressings only are required to balance removals in the crop (Anon., 2000).

Data from the Emley site allow an examination of the effect of manure/sludge additions on soil PK status. This was not possible at Gleadthorpe because some plots received addition PK fertilisers and no trends were therefore obvious. However, other experiments at Gt have shown similar relationships between manure applications and PK build-up: e.g. Shepherd & Withers (1999).

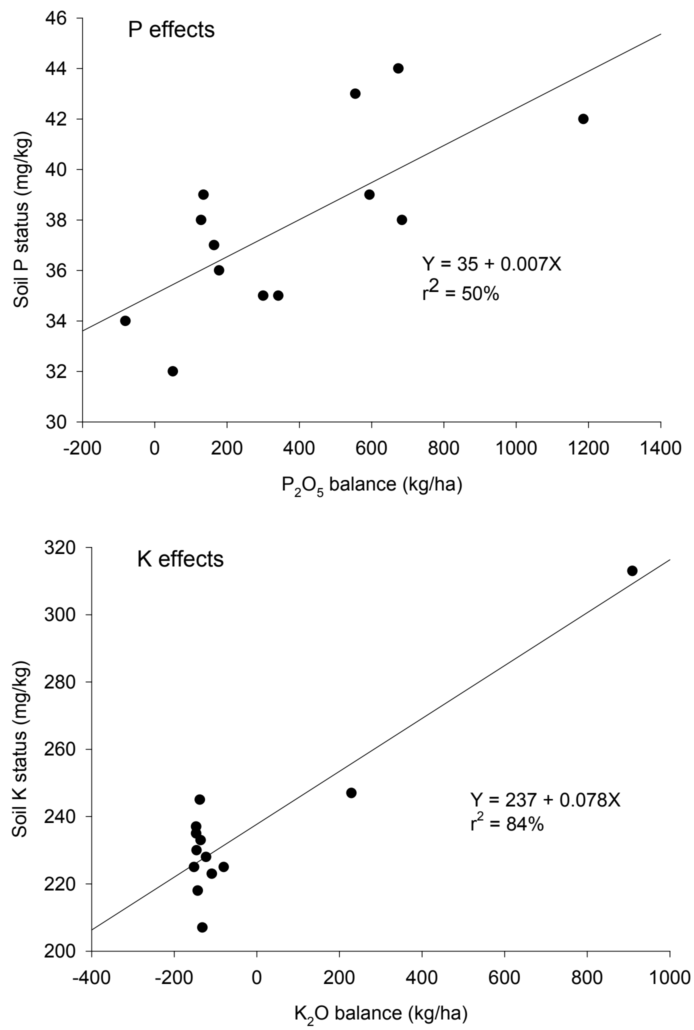


Figure 37. Emley: relationship between nutrient balance over three years and change in soil nutrient status.

Figure 37 shows the relationship between soil P status and P balance over three years for plots that received nil, 250N or 750N manure/sludge applications. The data show a linear relationship, also reported by Smith *et al.* (1998) for a range of manures. Typically, the slope of this line is 0.02-0.03, which translates to the need for a positive balance of 400-600 kg/ha P_2O_5 to raise the soil P status by 10 mg/l (Archer, 1985). The practical outcome of this is that it takes a long period of over- or under-fertilising to impact on soil P status. This should provide further evidence for the safety of the approach of using standard nutrient figures when reducing fertiliser inputs after manure applications (as discussed earlier). Interestingly, the slope of the relationship for these Emley data was *c.* 0.007, which is equivalent to >1000 kg/ha P_2O_5 applied to raise the soil P status by 10 mg/l.

The spread of data points for soil K was less than with P because all of the sludges contained only trace levels of K, and the relationship is greatly influenced by the K supply from the two FYM rates that were monitored (Fig. 37). Results therefore have to be treated with caution, but the Figure above shows the relationship between soil K status and K balance over three years for plots that received nil, 250N or 750N manure/sludge applications. The slope of the line (0.08) equates to a positive balance of about 600 kg/ha K_2O to raise soil K status by 50 mg/l. Although the K trends are unduly influenced by the FYM treatments and it would be unwise to draw strong conclusions from these data in isolation, this relationship agrees well with other experiments, which have demonstrated a balance of 400-600 kg/ha K_2O to raise soil status by 50 mg/l extractable K (Shepherd & Withers, 1999; Shepherd, 2001). The slow change in soil K status with K balance supports the approach of using standard values of manure K content in fertiliser planning. The slow change in soil K status with K balance similarly supports the approach of using standard values of manure K content in fertiliser planning.

Thus, in most circumstances, a simple balance sheet approach can be used to manage PK fertiliser policy, i.e. balancing inputs in manures and fertilisers with off-takes in harvested crop (Anon., 2000). At soil levels of P and K where it is acceptable to use this approach, it is also acceptable to use the total (rather than available), P and K content of the manures in the balance calculation.

A problem of regular manure applications to a single field is the imbalance between the N:P ratio of the manure/sludge and the crop. The ratio of nitrogen to phosphate was, on average, about 1:1 for dewatered cakes and 1.5-2.5:1 for manures and liquid digested sludges. This compares with a ratio of about 7-11:1 for most cropping situations (Anon., 2000; Karklins *et al*., 2001). Consequently, even though annual manure/sludge applications would be permissible under current NVZ legislation, this would lead to a build up of P (and, for manures, K) in the soil, with possible adverse environmental effects for surface waters in the event of erosion or surface run-off to nearby streams/rivers.

6.5. Economics

6.5.1 Fertiliser savings

Savings from manures are usually calculated in terms of NPK fertiliser replacement values. However, it should also be remembered that these materials are valuable sources of other nutrients. Sulphur deficiency of crops is increasing and manures are a useful source of S (Anon., 2000). Many farmers also value the organic matter, though it is difficult to place a financial value on this. Fresh additions of organic matter are important for increasing biological activity (Shannon *et al*., 2002) and for improving soil structure (Tisdall & Oades, 1982). Frequent applications are required to produce measurable changes in soil organic matter content. However, 'young' organic matter, as in fresh manure applications, is particularly important for aggregate stability in soils (Shepherd *et al*., 2002b). Therefore, manure applications at sensible agronomic rates may well benefit structure, providing that there is no damage during manure application.

Table 45. Calculated financial value of manure/sludge applications when applied at a rate to supply 250 kg/ha N (*over 3 years for solid manures).

Manure	Application time	Total N (kg/t)	FRV* (%)	P_2O_5 (kg/t)	K_2O (kg/t)	Savings (£/ha) N	P(K)
YW1	autumn	7.1	12	8.4	1.0	9	111
YW2	autumn	8.3	23	7.3	0.6	17	81
YW3	autumn	10.1	12	11.3	1.1	9	103
ST1	autumn	10.1	24	9.3	0.4	18	83
ST2	autumn	9.8	10	13.2	0.6	8	121
FYM	autumn	5.9	13	3.5	10.7	10	143
Pig slurry	autumn	4.2	16	2.1	3.7	12	88
	spring		47			35	88
Cattle slurry	autumn	3.2	13	1.3	3.3	10	86
	spring		24			18	86
LDS1	autumn	2.7	12	2.1	0.31	9	74
	spring		28			21	74

Table 45 shows estimates of the NPK value of the manures/sludges applied in this project. Thus, our starting hypothesis that savings of £80/ha can be made is sound. However, these do not take account of the spreading costs, which are considered later. To make the full savings, this requires farmers to take full account of the fertiliser value, as discussed earlier. It can be seen that a large proportion of the saving comes from P and K, especially for the solid manures. Table 46 shows that a single application of manure can supply the phosphate needs of cereal crops for several years. At a similar application rate, FYM (but not sludges) would supply sufficient potash for about 80 t/ha wheat (straw left on the field) or 40 t/ha where the straw was baled.

Table 46. Typical total yield of wheat (tonnes) required to remove all of the P applied in sludges/manures, with and without straw removed from the field. Assumes sludges are applied at a rate sufficient to supply 250 kg/ha total N.

Manure	P_2O_5 applied kg/ha	Cereal yield (t/ha) Straw baled	Straw inc.
YW1	296	34	38
YW2	220	26	28
YW3	280	33	36
ST1	230	27	30

ST2	337	39	43
FYM	148	17	19
Pig slurry	126	15	16
Cattle slurry	101	12	13
LDS	195	23	25

The importance of correctly accounting for manure N is not only in fertiliser value, but also in environmental effects – over application increases nitrate leaching after harvest. There are also potential quality effects on crop produce related to N applications (see below).

6.5.2 Yield and quality

Over-fertilising with N, for example, by not taking full allowance of the manure N supply, has consequences for crop quality as well as yield. In many cases, effects on quality will be more damaging in increasingly competitive markets. In the small plot experiments, the aim was to measure N supply from the manures and so no additional fertiliser N was applied to these plots. Consequently, we did not experience crop lodging. Because we took full account of manure N supply when calculating fertiliser additions at the demonstration plots, we similarly did not encounter lodging.

However, Figure 38 (Nicholson *et al*., 1999) shows what can happen if fertiliser N inputs are not correctly adjusted (downwards) after manure application: lodging increases, yield decreases and crop quality may also be adversely affected.

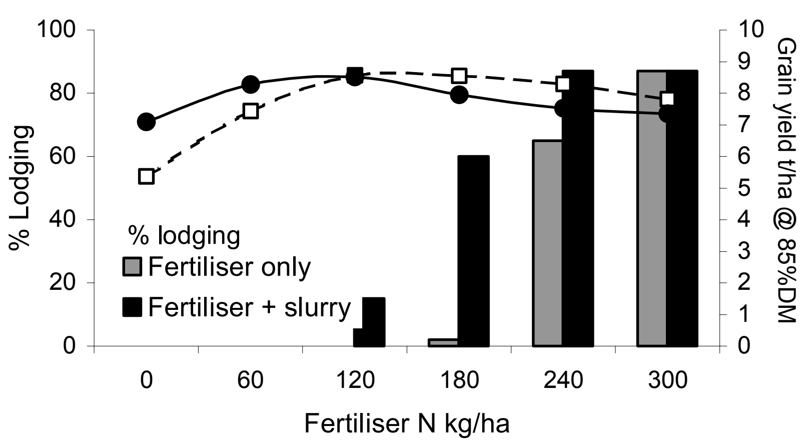
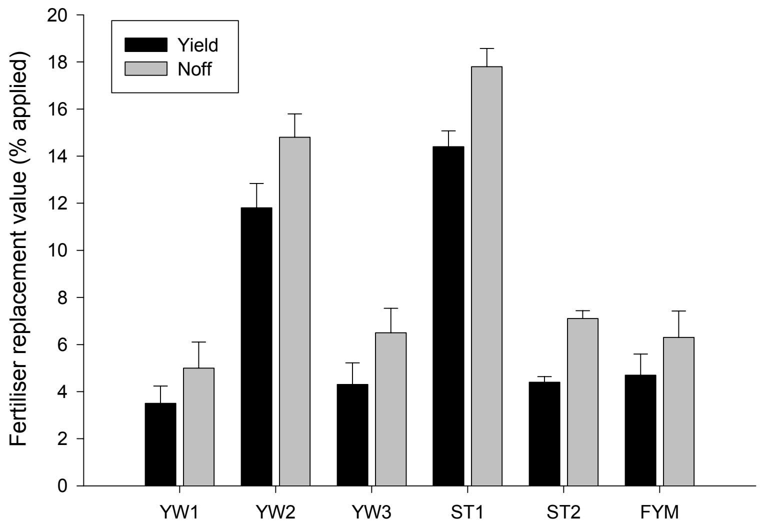


Figure 38. Fitted grain yield response curves and crop lodging for winter wheat grown with and without cattle slurry top dressed in spring (ADAS Bridgets, 1992); yield with slurry – closed circles; yield without slurry – open squares (Nicholson et al., 1999).

As discussed earlier, the manure/sludge applications had no adverse effects on grain metal concentrations.

Data from the Gt site showed an indication of a benefit to grain N concentrations in the first harvest after application of the manure/sludges. This might be expected: we have already discussed the slow release nature of N from the organic fraction. If N is released during the grain filling period this might therefore benefit grain protein levels. The experiment was not designed specifically to test for this effect, so the method for observing the effect was indirect and only at one site in one year (no data for Emley in the first year after application). FRV was calculated from both yield response and grain N off-take (Fig. 39).



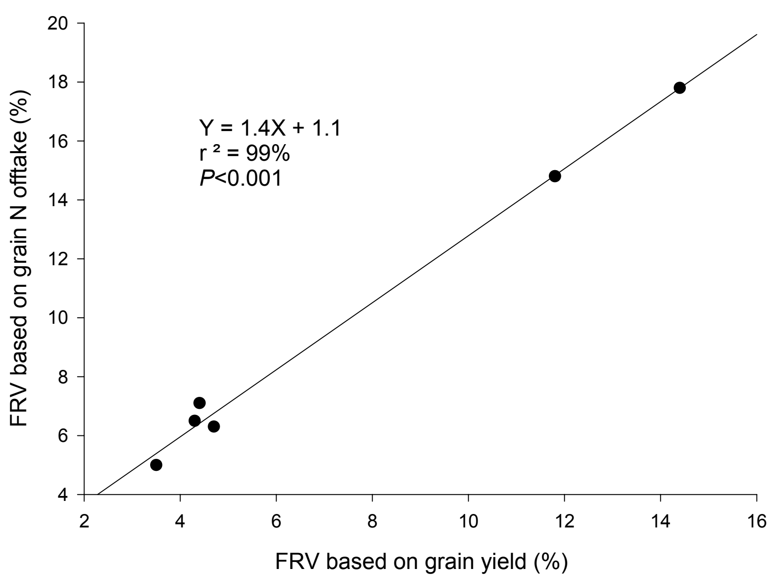


Figure 39. Upper histogram: comparison of Fertiliser Replacement Value (FRV) calculated from yield and grain N off-take (with standard errors). Lower graph: relationship between FRV calculated from yield and grain N off-take.

For all manure/sludges, FRV calculated from grain N off-take was larger than when calculated by yield. A paired t-test showed the difference to be highly significant. A regression analysis shows that FRV(N off-take) was about 20% greater than FRV(yield). This suggests continued N uptake into the grain-filling phase, which warrants further examination in more detailed experiments.

6.5.3 Spreading costs

Although it is straightforward to estimate the monetary value of the nutrients in manures and sludges, there have been few attempts to evaluate the costs of spreading the materials. Prototype decision support software, **SPR**eader **E**conomic **A**ssessment and **D**ecision **S**upport, (SPREADS) has recently been developed and is capable of assessing the costs and performance characteristics of different manure handling systems (Smith, 2001). This package was used with nutrient data from this project to test a range of manure handling options (Table 47, Fig. 40). Costs of the scenarios studied varied between £1.25/m^3 and £2.10/m^3 of liquid manure, depending on the application method. However, the figures given are examples only and the estimated costs are much influenced by farmer preference, system design and, in particular, by the size of the enterprise and the amount of manure to be handled.

For liquids, it can be seen that shifting to a spring application increases the value of the materials (better N use efficiency, as discussed earlier), but there comes with it additional spreading costs, mainly related to the purchase of specialist equipment for top-dressing the crops. For none of the scenarios tested for cattle slurry does the NPK value completely recoup the spreading cost. The reverse was true for pig slurry, mainly because of its larger available N component. Liquid digested sludge was similar to cattle slurry in costs.

Table 47. Potential nutrient value of slurries and liquid sludges, as used in the experiments and based on notional outputs of large dairy or pig units and estimated costs of application under different strategies.

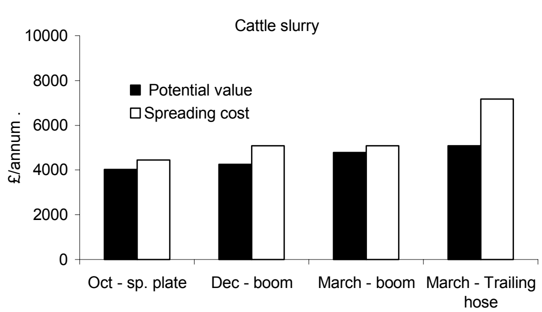
		Cattle slurry	Pig slurry	LDS1
	No of animals[1]	200	200	-
	No of finished pigs	-	4600	-
Total slurry/sludge	(as produced) m^3	2304	2151	
Total slurry/sludge	(with dilution) m^3	3456[2]	4302[3]	4000
Potential value (£)[4]	- Oct [5]	4027	6598	3214
	- Dec [5]	4259	7195	3570
	- Mar [5]	4790	8333	4315
	- Mar –t.hose [5]	5089	8767	4542
Spreading costs (£)[6]	Oct surface b/c	4451	5135	4890
	Dec – boom appl.	5079	5729	5496
	Mar – boom appl.	5079	5729	5496
	Mar – t.hose	7165	7624	7461

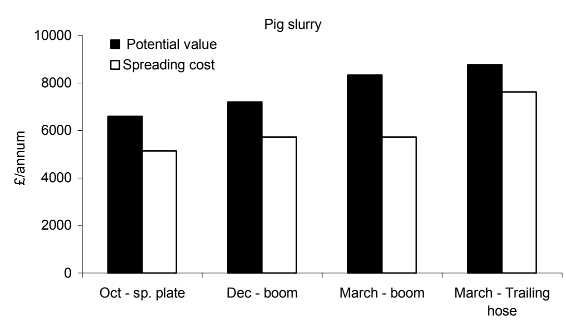
Notes:
[1] No. of adult animals; milking cows; breeding sows (latter assumed on straw system).
[2] Based on estimated excretal output, with additional washing water & dirty water run-off (1:1.5 dilution).
[3] Based on estimated excretal output, with additional washing water & dirty water run-off (1:2 dilution).
[4] Based on average fertiliser prices, with N = 30p/kg; P_2O_5 = 30p/kg; K_2O = 20p/kg.
[5] Differential N values estimated using MANNER (ver 3.0), for slurry/sludge analysis, application technique, soils and typical rainfall (averaged across Rosemaund, Hattons and Bedale.
[6] Spreading costs estimated using the SPREADS (ver 2.0) DSS (Smith, 2001).

However, it should be noted:

- For liquid manures produced on-farm, there will be a handling/spreading cost anyway, so doing the job well will make the most of the nutrient value.
- For sludges, Water Companies usually cover the cost of spreading, so that there is minimal cost to the farmer.

Similar calculations were made for solid manures (Fig. 41). In this case, costs varied between £2.00/t - £3.30/t of handled manure. Again, pig FYM showed a large benefit of NPK value over spreading costs, whereas the other materials approximated to cost neutral when using a single spreader.





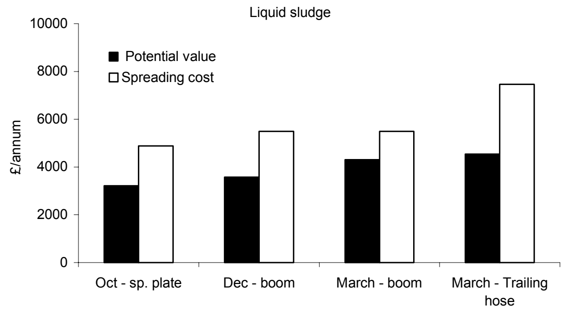
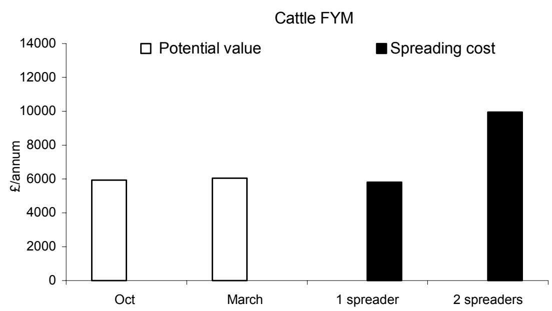
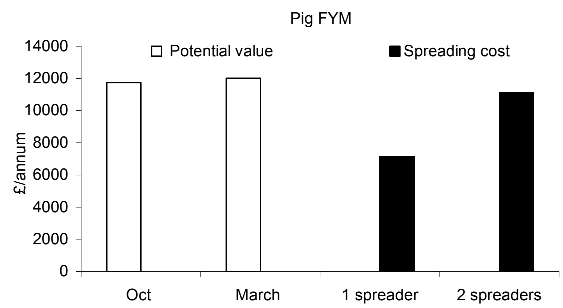


Figure 40. Comparison of potential fertiliser replacement value of cattle and pig slurries used in the experiments, with estimated costs of application by broadcast on stubble (autumn), top-dressing via boom + splashplate (winter or spring) and trailing hose in spring.

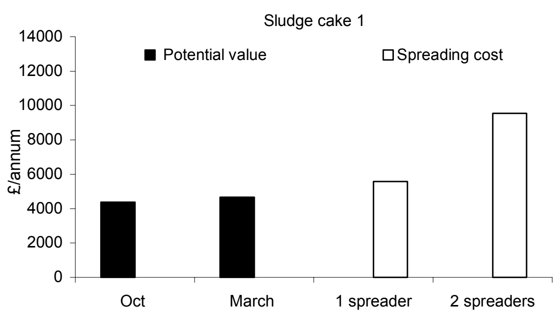
(a) Cattle FYM



(b) Pig FYM[1]



c. Sludge cake (ST2)



(d) Sludge cake (YW3)

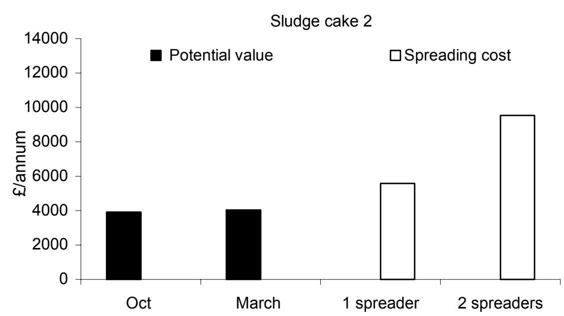


Figure 41. Comparison of potential fertiliser replacement value of cattle FYM and sludge cakes used in the experiments, with estimated costs of application by spreading on stubble (autumn), or in the spring. The option of using one or two manure spreaders is considered. ([1]Potential value of Pig FYM based on 'standards' for nutrient content, as this material was not used in project).

6.5.4 Risk and risk management

Fertiliser usage statistics suggest that many farmers are averse to risk when planning fertiliser use after manure/sludge applications. We have already argued that the risk of yield loss from reducing P and K inputs after manure is very small, and we have hypothesised that most of the perceived risk is from under-fertilising with N given the crop's likely large response to this nutrient.

The main source of risk to the farmer is loss of yield and quality from under- or over-fertilising following manure applications, brought about due to:

- Variability in manure N content;
- Uneven spreading of manure.

Some of this risk is immediately reduced by adopting a manuring strategy that aims to supply no more than half of the crop's need from manure application (e.g. Fig. 42). In practice, following the Water Code or NVZ regulations ensures this for most crops by limiting the total N application from manure that can be applied in one year.

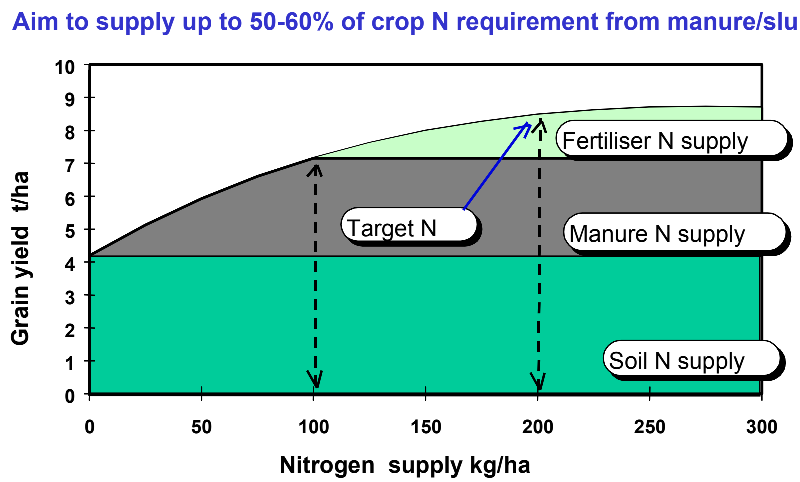


Figure 42. Suggested strategy for combining manure and fertiliser N applications.

Table 48. Estimated effects on N supply for selected manures of using 'standard' figures for N content and the range of N content values in this project. Liquids applied at 50 m^3 in spring and solid manures applied at 30 t/ha in autumn.

Manure	Range of N content	Total N (kg/ha)	Nleached (kg/ha)	Nvolat (kg/ha)	N supply (kg/ha)
Cattle slurry	minimum	95	0	6	53
	RB209	150	0	16	66
	maximum	195	0	30	80
LDS	minimum	32	0	2	29
	RB209	100	0	9	55
	maximum	190	0	11	62
Cattle FYM	minimum	150	2	0	15
	RB209	180	14	3	16
	maximum	182	2	0	19
Dewatered Cake	minimum	201	26	6	17
	RB209	225	26	6	20
	maximum	315	75	17	24

Data from this project allowed a quantification of the first risk (i.e. variability in nutrient content). To test this, we examined the nutrient analyses to find maximum and minimum N contents for cattle slurry, cattle FYM, liquid digested sludge and dewatered sludge cake, and compared these with standard values from RB209. The following assumptions were then made:

- Liquid manures applied 1 March at 50 m^3/ha to a loamy sand;
- Solid manures applied at 30 t/ha on 1 October to a loamy sand.

The MANNER model was then run to allow estimation of fertiliser N values for each of the manures, summarised in Table 48.

In this example, the imprecision in N supply as a result of variability in nutrient content can therefore be seen to approximate to a range of +/- 20 kg/ha N for liquid manures and +/- 10 kg/ha N for solid manures. Thus, the risk of over- or under-fertilising is small in practice. Using the yield response curve from, for example, Gleadthorpe 1999 (Fig. 7) the yield penalty from under- or over-fertilising was then calculated, compared with fertilising at the optimum rate. It might be argued that this is a false test given the difficulty in accurately predicting the optimum fertiliser response of a crop in a given season in a given field. However, given the shape of a typical N response curve, it could be argued that the recommended N rate should be close to the yield plateaux anyway.

Table 49 shows the yield change (Δy) from the optimum assuming an under- or over-fertilisation of 10-30 kg/ha due to variability in manure N analysis. Note that the +/- 30 kg/ha is outside the range we would have expected, based on the variability of the manures used in the project, but is included as a worst case example.

Table 49. Yield change (t/ha) from fertilising above or below the optimum.

Fertiliser change (kg/ha N)	**Δy (t/ha)**
-20	-0.12
-10	-0.05
0	0
10	0.03
20	0.03

This is an important conclusion: by taking full allowance of the N fertiliser value of a manure application, even using standard data for manure N composition, the risk of yield loss is relatively small.

However, the real risk to the farmer comes from not making an allowance for the manure N applied, or only a small allowance. Obviously this risk increases if the manure in question is a manure with a high proportion of available N, such as a slurry or a liquid digested sludge (or poultry manure). Table 49 shows that, for example, cattle slurry applied according to our scenario provides a fertiliser value of 66 kg/ha N. If a farmer only makes an allowance of, say, 16 kg/ha (the typical allowance from annual statistics on fertiliser usage, Chalmers *et al*., 1998), then there is a potential for over-fertilising by 50 kg/ha N compared with fertilising in the absence of manure. The yield and quality losses from this practice will depend on how well the crop stands, but data from the Bridgets example (Fig. 38, above), suggest that yield losses could be 0.5-1.0 t/ha, plus losses to quality associated with lodging.

So, again, the conclusion is important: the losses (in terms of quality and yield) from not taking full account of the N supply following an application of manure (particularly a liquid manure or poultry manure) are potentially larger than those likely to arise as a consequence of any imprecision associated with following the recommended practices as published in, for example, RB209.

It is also possible to estimate the environmental effects of over-fertilising by 50 kg/ha N. Numerous workers have now reported the upturn in nitrate leaching losses if N applications exceed the crop's optimum requirement (e.g. Goulding, 2000). Leaching losses with incremental N applications follow a broken stick model, with only small increases up to the optimum (a slope on this line of about 5%

for cereals), and then a large upturn after the optimum (a slope of *c.* 75%). Consequently, over-fertilising by 50 kg/ha N could increase leaching by 40 kg/ha N.

Again, this is an important conclusion: it is often thought that the main risk of nitrate leaching from manures coincides with the winter of their application. However, a major source of leaching loss can occur in the following winter and derives from over-fertilising the crop.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

7.1.1 Nitrogen fertiliser replacement value (FRV)

- A reliable recommendation system needs to take account of N inputs from manure, loss processes and mineralisation of organic N into plant available forms. For the solid manures used in this project (old, composted FYM, dewatered sludge cakes and their products), the organic N component was large and good quantification of the organic component was important. The project included composted manure and dewatered cakes for which there was little published information.

- Results showed that, in the first year, an amount of N equivalent to 15% or 5% of the organic fraction was mineralised and contributed to the FRV of the manures for fresh digested dewatered cakes and composted manures/cakes, respectively. The smaller mineralisation factor for composted materials was confirmed by the results of the laboratory incubation experiments. Clearly, much of the initial degradation of labile N had occurred during composting prior to land application.

- Results also showed a significant residual contribution into the second and third years of application. This is currently not accounted for in existing recommendation systems.

- This 'rule of thumb' (5% and 15%) represents a good start in improving fertiliser recommendations, but a more detailed quantification is required if it is to be incorporated into Decision Support Systems and be applied to crops with different lengths of growing seasons. The indications are that the mineralisation is related to thermal time and relationships agree well with independently calculated algorithms for cattle FYM.

- Laboratory incubations were a good method of assessing whether a manure was likely to be a slow or rapid N mineraliser. C:N ratio was not a good guide. Perhaps this is not surprising given that the recalcitrance of organic matter is as important as its C:N ratio. NIRS offers potential as a rapid analytical tool.

- Two other important practical aspects of the slow release nature of the organic N were noted:

  - There was a suggestion that the manure applications increased grain protein levels. This might be due to N mineralised during the grain filling period. However, a separate project is required to explore this more fully.

- Three manure application rates were tested: 250, 500 and 750 kg/ha N. The highest rate (outside current Codes of Practice) of dewatered cakes left a large post-harvest soil mineral N residue in the autumn after application. This was probably due to mineralisation after crop senescence and therefore presented an increased risk of nitrate leaching in the following winter. Such a high rate cannot be recommended, therefore.

- Liquid manures provide a rapidly available source of nitrogen, mainly attributable to their ammonium-N content, which in these studies represented 60, 50 and 40-50% of the total N content of pig slurry, cattle slurry and liquid sludges respectively (values very close to the published 'standards').

- The mineral (NH_4) N content of liquid manures is vulnerable to loss – initially, rapidly by volatilisation as gaseous ammonia and, subsequently, if applied late or outside of the growing season, by nitrate leaching. Ammonia losses following application are particularly influenced by manure analysis (NH_4-N and DM content) and by application method (though these parameters were not studied in detail within this project). Losses by nitrate leaching, particularly where manures are applied to freely draining soils, depend on the amount of rainfall and, hence, the volume of drainage following the application.

- The FRV% of liquid manures was particularly dependent upon time of application, with spring top dressing (on cereal crops GS24-31) allowing the best opportunity for optimum utilisation. Later applications were used less efficiently, partly as a result of reduced opportunity for crop uptake of manure N and, partly, as a result of foliar scorch.

- Where losses of N are unavoidable, they need to be estimated and taken into account when trying to allow for the contribution from manures. Often, much of the readily available N from an autumn application of a liquid manure, will be lost by nitrate leaching. However, a substantial loss does not imply a <u>nil</u> contribution from the manure N. For example, an average 10% efficiency was obtained in this work, for slurry and sludge applied in the autumn. This would represent *c*. 25 kg/ha N from an application supplying 250 kg/ha N and worth >£8/ha, for the N alone.

- MANNER provides a means of understanding and quantifying possible N losses following application and of estimating the potential contribution to crop N requirements. Based on the results of this research, it was concluded that, with accurate information on manure type, analysis and application rate, MANNER can provide a reliable estimate of manure N supply.

7.1.2 Nutrient variability and risk

- Variability in the nutrient content of manures is often cited as a reason why nutrient value is not fully accounted for when planning inorganic fertiliser inputs after manure. Data from our project confirmed that there is some variability over time between manures/sludges, even from the same source. Methods for dealing with this variability include:
  - Use of standard figures for nutrient content (e.g. as published in RB209) – satisfactory for planning purposes and for use in the medium-term, particularly for P and K;
  - Use of laboratory analysis of the manures;
  - Use of on-farm methods for assessing the N content of liquid manures (a rapid method).

- An analysis of risk associated with yield loss and quality was undertaken using data from this project. The analysis showed:
  - Although manure N content was variable, the possible penalties from using standard values for manure nutrient content were small compared with potential losses in yield and quality from over-fertilising by making little or no reduction in N inputs after manure;
  - Risk of yield loss from P and K applications was minimal. Use of standard nutrient figures was acceptable because soil P and K status changes only slowly, even if consistently under-fertilised. Also, there is the 'safety net' of soil analysis, say, every five years to monitor the situation.

- The risk of yield loss from under-fertilising increased with manures with a large proportion of readily available N (slurries, liquid digested sludges and poultry manures). However, there are on-farm methods for measuring the readily available N component, as described above. Water Companies also provide an analysis of the sludge. This should include a measure of the ammonium-N component to be of use.

- An assessment of spreading costs and efficiency of spreading operations was also made using the recently developed DSS system, SPREADS. Costs of spreading in the scenarios studied varied from £1.25/m^3 to £2.10/m^3 for liquids and from £2.00/t to £3.30/t for solids. However, costs (and efficiency) are very sensitive to a range of influencing factors, including the infrastructure and layout of individual farms, distances to fields, farmer preferences, numbers of spreaders and time available for spreading.

7.1.3 Environmental issues

- Nitrate leaching risk from autumn manure application is greatest from manures with a large proportion of readily available N. Hence, the existing NVZ regulations on closed windows of application for liquid manures on sandy and shallow soils.

- The project showed a nitrate leaching risk from composted materials with an elevated nitrate content. Nitrate contents of manures are generally small, but composting under aerobic conditions can cause accumulation of nitrate. This risk may become more of an issue if composting and the application of compost become more widespread.
- Shifting liquid applications in to late November, compared with September, decreased nitrate leaching losses.
- Ammonia losses are particularly a risk with liquid manures and poultry manures. Losses can be substantially reduced using surface banding or placement techniques for liquid manures that also increase the precision of application. Solid manures should be incorporated within 24 hours of application, but any conserved N may be lost by subsequent N leaching, where applications are to freely draining soils in the autumn.
- A contribution to avoiding eutrophication is to avoid P accumulation in soils. Thus, it is necessary to take full account of P applied in manures and reduce fertiliser inputs accordingly. Prevention of erosion by good soil management is also key.
- Metal contents of the sludges were generally low (with the exception of one sludge from an historically industrial catchment). We observed no detrimental effects from applications of sludge to the soil. Grain metal concentrations were often below the analytical limits of detection. Generally, sludges are becoming cleaner, and there are legal requirements to monitor soil and sludge metal contents.

7.2. Recommendations

1. The project has shown that top-dressing of liquid manures on to growing cereal crops in the spring is a useful technique that could be adopted more widely. This is particularly relevant to farm slurries, and the options and opportunities need to be promoted more widely.
2. Poultry manures offer the advantage of a large proportion of readily available N. Small plot experiments have shown that this can be top-dressed, but there is a lack of suitable commercial equipment capable of applying sufficiently low rates for compliance with the NVZ regulations that are compatible with 12 m wide tramline systems, which is currently beyond the performance of the current generation of solids spreaders.
3. We have gathered considerable information on the N mineralisation dynamics of a range of organic materials. Whereas we now have ‘rule of thumb’ mineralisation factors for these materials, the data have to be incorporated into recommendation systems if they are to be used across a range of cropping and soil-type conditions. Two separate initiatives are underway

(MANNER-NPK and SNSCAL) where the information will be used to refine fertiliser recommendation systems.

4. The project has shown that nitrate can form a substantial proportion of the readily available N fraction of composted manures. This is currently not accounted for in recommendation systems but needs to be included when the recommendation systems are next reviewed.

5. Water Companies analyse sludge as a routine. This offers potential advantages when calculating a fertiliser value, but the following steps need to be introduced to make full use of this information:

- Include ammonium-N and nitrate-N in the analysis suite;
- Link to a reliable recommendation system to provide an estimate of nutrient value of the sludge. This could be MANNER, after updating the mineralisation algorithms.

6. The potential effects of organic manures on grain protein levels warrants further examination.

7. NIRS offers potential as a rapid method of total N determination but relies on building a sufficiently large dataset to allow correlation between wet chemistry methods and spectra.

8. TECHNOLOGY TRANSFER

A strength of the project has been the large element of technology transfer undertaken during the project, though this will continue afterwards also. The outputs have been various, as detailed below. A major focus of the project was to have been the demonstration sites. These attracted over 200 farmers in total. Because this was a focused event, they had come to the demonstration days specifically to learn of the results of the project.

The Open Days provided the opportunity to collect some information from farmers and consultants attending the events. In the first instance, this covered their interests and concerns, as well as gauging their skills and level of awareness about the nutrient 'strength' of manures.

8.1. Articles/papers/presentations

(a) Open Days

- Project Open Day, Bedale, May (120 visitors)
- Project Open Day, Wolverhampton, May (105 visitors)

Correct allowance for the nutrient content of animal manures in fertiliser planning can save farmers considerable expense in their use of mineral fertilisers. However, accuracy in the estimation of the quantity and nitrogen (N) content of manures applied is generally poor. Recent research suggests that knowing accurately the rate of manure applied is more important than high precision in spreading. In order to encourage greater awareness of the value of organic manures to crop rotations and fertiliser planning, a competition to estimate the quantity of FYM or digested sludge cake in a loaded trailer or spreader was set up at the above events. A cross-section of farmers and others in the industry had the opportunity to participate.

At Coven, a rear discharge manure spreader was fully loaded with digested sludge cake and visitors invited to estimate the weight of it's contents; at the Bedale site a trailer laden with cattle FYM was used. A supplementary question sought a judgement on the relative nitrogen contents of cattle slurry, turkey litter, sewage sludge cake, and FYM. Further questions invited a view about the severity of problems facing farmers attempting to recycle manures in a responsible manner.

Preliminary assessments of the results have been made and the data relating to the "guess the weight" competition are summarised in the table. A total of 68 completed entries was received, of which 65% were from farmers or farm staff, 4% students, 24% consultants/technical staff, and 7% contractors.

Significant time and effort seemed to be invested by participants in calculating the weight of manure in the spreader, but results, on average, were higher than the true value (sludge cake - 60% overestimate; FYM – 40% overestimate). Overall, 66% of entrants realised that turkey litter is likely to contain the most and 60% that cattle slurry contained the least nitrogen content of the materials listed, but there was confusion (only 30-40% correct) about the relative strengths of sewage sludge cake or FYM (Fig. 43). Assessing potential problems facing farmers attempting to make good use of organic manures, knowledge of manure nutrient content and allowing for nutrient losses following application, were considered the major problems with average scores of 3.4 and 3.8, respectively when considered on a scale of 1 (no problem) to 5 (very difficult) (Fig. 44). Overall, there appeared to be a high level of satisfaction with the perceived level of usefulness and relevance of the event (the person who scored this part of the questionnaire "1" was a student who had indicated privately that she had not wished to come to the event with her colleagues).

Table 50. Summary of competition answers.

	Wt. of spreader contents (tonnes)	
	Coven	**Bedale**
Actual	7.93	3.22
Competition estimates:		
Mean	11.27	5.10
Over/under estimate	+ 42%	+ 60%

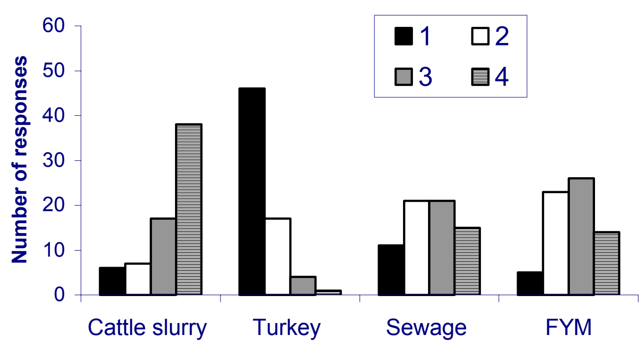


Figure 43. Number the manures (1-4) in order of nitrogen content (kg/tonne) (with 1 = highest and 4 = lowest N content). Proportion of correct responses – Cattle slurry 56%, Turkey litter 67%, sewage cake 31%, FYM 38%.

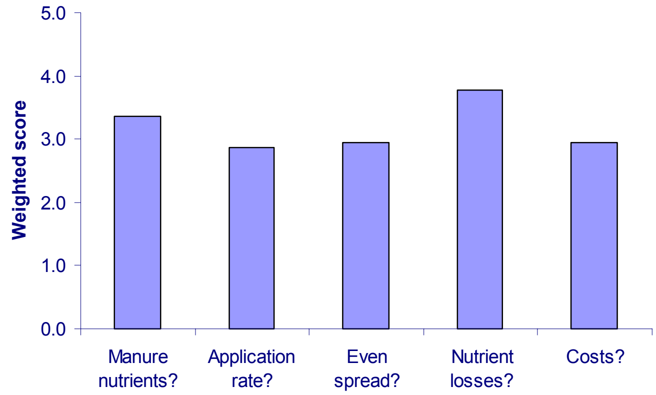


Figure 44. What do you consider to be the greatest problems in using manures and reducing use of chemical fertilisers (1= no problem to 5+ very difficult).

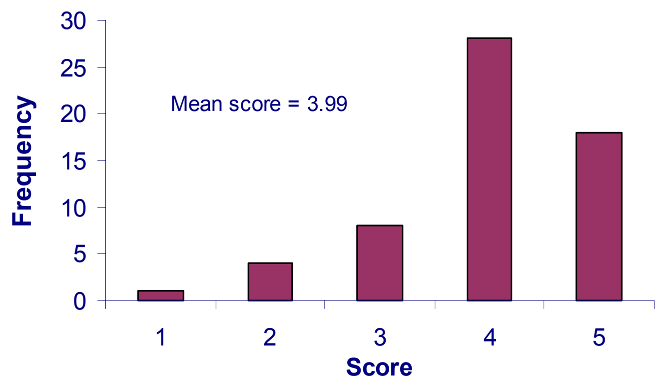


Figure 45. Relevance and usefulness of the event. Please rate from 1 (poor) to 5 (very good).

(b) Other events at which the project was presented:

– Cereals 2000, Lincoln, June (poster on the HGCA stand);
– Presentations of progress and results within the programme of meetings arranged during the year as a part of the MAFF (Defra) Demonstration Farms project, "Making the Most of Manures" (perhaps 12-15 meetings, with attendance varying between 10-50);
– Aqua-Enviro Conference, Wakefield, November 2000(*c*. 200 delegates);
– AAB Conference, Cambridge, December 2000 (*c*. 200 delegates);
– Presentation at HGCA Roadshows, winter 99/00 (Stafford, Morpeth and Antrim – total *c*. 200 attendees) and Topic Breakfast (Wrekin Farmers Telford – *c*. 30 attendees);
– HGCA Roadshow Aberdeen, December 2001 (*c*. 80 attendees);
– SRI "MEASURES" Project, Presentation of Results to Stakeholders meeting, Feb, 2002;
– LEAF/HGCA Farm Open days, Wallingford, (*c*. 35 farmers); Driffield, Yorks (*c*. 30 farmers);
– Cereals 2002, Sleaford: own plots and marquee.

(b) Written publicity

- Article in "Widespread", Severn Trent Magazine, Spring 1999.
- HGCA Project Progress No. 6(2000): *Using animal manures on arable crops*.
- LINK Research Leaflet (1999): *Organic amendments as nutrient sources in arable rotations*.
- Conference papers (AAB and Aqua-Enviro) relating to the conferences described above (see below).
- Handouts for the HGCA Roadshows described above.
- EA-funded leaflet promoting results of the project (2002): *Best use of manures and sludges for arable crops*
- HGCA Topic Sheet Number 64 (winter 2002/03): *Using manures and biosolids on cereal crops*.

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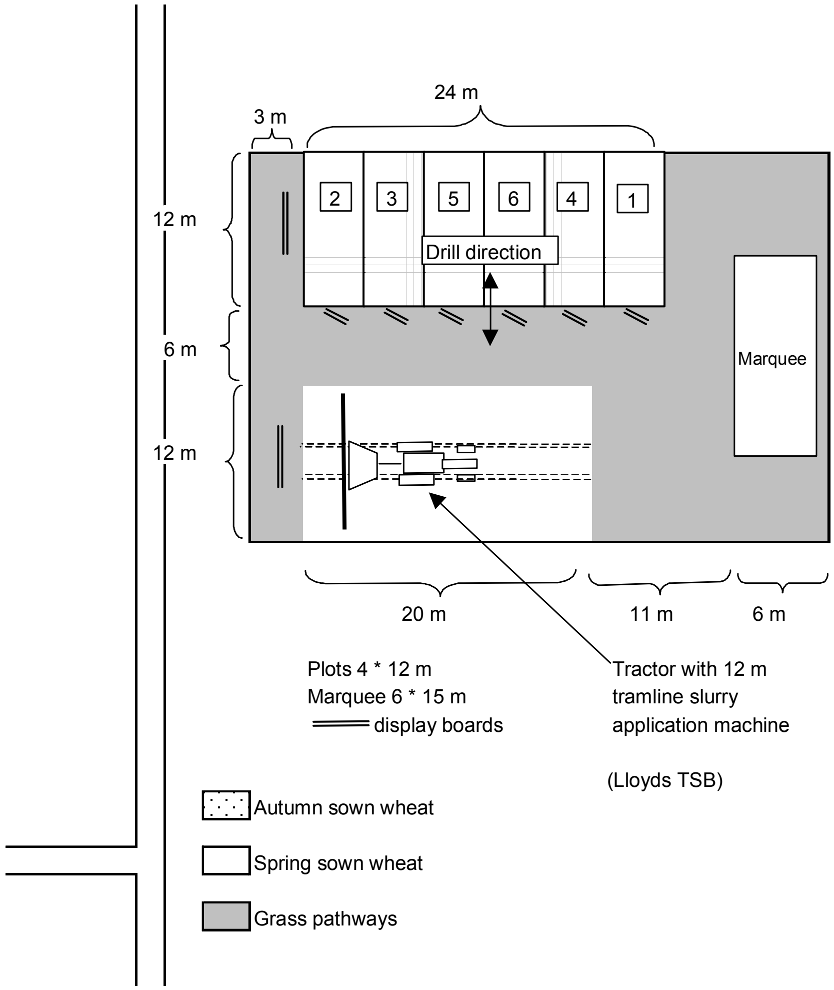
(c) Press articles

There have been a number of press articles featuring the project, based around the Demonstration Days. There have been at least 5 large articles including features in Crops, Farmers Guardian and Farmers Weekly and Pig Farmer. Also a short article in Farmers Weekly following interviews with Edward Long at CEREALS 2002.

8.2. Demonstration Sites

Layout and detail of the stand at CEREALS 2002 is shown below.



Treatments

1 Control - no fertiliser, no manure.
2 Fertiliser only - split dressing GS24 and GS 30.
3 Autumn FYM, incorporated pre-drilling, plus strategic fertiliser N.
4 Autumn de-watered sewage sludge cake, incorporated pre-drilling, plus strategic fertiliser N.
5 Spring cattle/pig slurry - surface broadcast, March, plus strategic fertiliser N.
6 Spring liquid digested sewage sludge - surface broadcast, March, plus strategic fertiliser N.

The stand was sited in an apparently favourable location, almost directly opposite the main entrance. Although the CEREALS event is generally seen as ‘high profile’, the total number of visitors to the stand over the two days was slightly disappointing, especially on the first day, and was estimated at just under 200. Some other stand-holders in the near vicinity reported similar feelings. The stand layout, with the marquee and information panels, literature and other display material towards the back of the stand, with plots and equipment nearest the pedestrian walkway (see image below) may have done little to encourage casual visitors. It is therefore possible that only those who specifically set out to visit the stand will have made the effort to actually cross the marquee entrance! Total attendance is unlikely to have been assisted either by the presence of ADAS on two other sites at the event with inevitable confusion to those trying to find specific technical information.

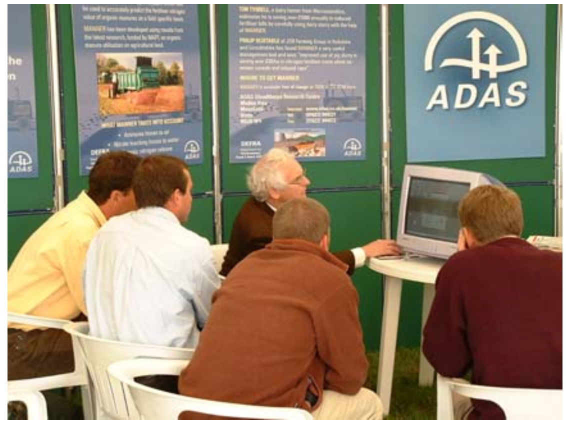
Nevertheless, the stand which had been intended as a replacement for the "demonstration and technology transfer" element of the project lost during 2001, (to the Foot and Mouth control measures) was seen as worthwhile. The stand was staffed, during the two days, by 1 senior officer from Severn Trent Water, 3 senior ADAS consultants, by Terry Baker from Tramspread and with partial assistance of Defra and HGCA personnel. Meaningful contacts and discussions, over the two days were estimated as follows:

Farmers/consultants/trade	140-170
International	6
Students	15-20
Press interviews	4
MANNER copies ordered	44

(a) General view of marquee and plots

(b) Visitors in the marquee

(c) Project panels on display



(d) Demonstration of MANNER software

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