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Mineralisation of organic nitrogen from farm manure applications

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Running Title: Manure organic N mineralisation

Abstract

This study aimed to quantify the amount of nitrogen (N) mineralised from the organic fraction of farm manures under field conditions. Nine different farm manures were stripped of their ammonium-N content prior to soil incorporation and establishment of ryegrass at two sites in England. Grass N uptake and nitrate-N leaching were measured for five consecutive seasons and compared with an untreated control, with the sum of N uptake + leaching (net of the control) used as an estimate of the amount of organic N mineralised from the applied manures. The amount mineralised was related to thermal time (cumulative day degrees above 5°C – CDD), with two distinct phases – an initial phase up to 2300 CDD (*c.*18 months under UK climatic conditions) where mineralisation proceeded at rates ranging between 0.005-0.027 %mineralised/CDD, and a slower phase at >2300 CDD, where rates were negligible at <0.001 %mineralised/CDD. There was no difference between soil types, both being light-textured (<20% clay), but there were differences between manure types depending on the manure C: organic N ratios. For pig slurry and layer manure (C:organic N = 9-12:1) up to 70% of the organic N was mineralised, compared to 10-30% mineralisation from the cattle slurry and straw based FYMs (C:organic N = 10-21:1).The relationships derived provide a useful tool for predicting both the amount and timing of manure N release, with important implications for both crop N uptake and leaching risk.

Keywords: Mineralisation, nitrogen, manure, organic matter, nitrate leaching, thermal time

Introduction

In the UK, around 93 million tonnes (fresh weight) of farm manures (cattle, pig and poultry manures) are recycled to agricultural land supplying *c*.405,000 tonnes of total nitrogen (N) annually (Nicholson *et al*., 2008). Typically, 75-90% of the total N content of straw-based farmyard manures (FYM) is present as organic N, 50-60% for poultry manures and 30-50% for slurries (Anon., 2010), with the remainder as readily available N (principally ammonium and uric acid-N for poultry manures). Research efforts have largely focused on manure readily available N forms, because in the short-term these have the greatest influence on crop N supply, ammonia volatilisation and nitrate leaching losses (Jarvis & Pain, 1990; Unwin *et al.,* 1991; Chambers *et al.,* 1997). However, in the longer-term manure organic N release will have an increasingly important effect on soil N supply, particularly in situations where repeated manure applications are made to land (Schröder *et al.,* 2007). If manure organic N release occurs during periods of crop growth (spring-summer) fertiliser N requirements will be reduced, but if release occurs during the autumn-winter period, nitrate leaching and denitrification losses are likely to be increased.

A key requirement of the Nitrate Vulnerable Zones Action Programme (NVZ AP) in England (SI, 2008) is for farmers to formally take into account the crop available N supply from livestock manure applications. This requires the use of manure N use efficiency (NUE) coefficients (or fertiliser replacement values) to calculate how much of the total N content of a livestock manure applied to their land will be available for the following crop. In England and Wales, these range from 10% for pig and cattle farmyard manures to 50% for pig slurry, with poultry manures predicted to have an NUE of 30% (Anon., 2013), based largely on analyses of their readily available N content with some allowance for losses (mainly via nitrate leaching and ammonia volatilisation). In a review of manure N use efficiency throughout Europe, Webb *et al*. (2013) reported that NUEs are commonly based on the N estimated to be available during the first growing season only and that most countries predict short-term mineralisation using a simple N model of the annual relative decomposition rates of manure organic N. They concluded that whilst longer term effects of organic N mineralisation are important and should be considered, this does not yet occur in the majority of EU Member States. .

One of the major challenges in determining the fertiliser value of manures is predicting how much of the manure organic N will mineralise both in the current and future growing seasons. Quantifying this is complicated by the presence of several N forms which differ between manure types, namely: mineral N (principally ammonium-N), readily mineralisable N (urea and uric acid for poultry manures) and more slowly mineralised organic compounds (e.g. lignin compounds). Indeed, Chadwick *et al.* (2000) showed considerable variation in the organic N content of fifty contrasting manure types (20 slurries, 20 FYM and 10 poultry manures), with cattle and pig slurry typically containing 29-35% of their total N content in organic forms, cattle and pig FYM 71%, and broiler litter and layer manure 71% and 54%, respectively. They also identified differences in the C:organic N ratios of the contrasting manure types, with cattle FYM typically having the highest ratio at 17:1, followed by cattle slurry and pig FYM at 14:1, pig slurry at 11:1, broiler litter at 9:1 and layer manure at 6:1.

It is widely recognized that organic materials with low C:N ratios tend to have higher rates of mineralisation than those with higher C:N ratios (Floate, 1970; Serna & Pomares, 1991; Aleef & Nannipieri, 1995). Thus, organic N release is likely to vary according to manure type and C:organic N ratio. It is also dependent on the activities of decomposer organisms, which are themselves influenced by their physical environment, with temperature a key controlling factor (Watts *et al.,* 2007; Whitmore, 2007).

Much of our understanding on the rate of mineralisation of manure N has been derived from short-term laboratory incubation or pot studies (e.g. Chadwick *et al*., 2000, Whitmore, 2007; Gil *et al*., 2011), which have often been complicated by the presence of variable amounts of mineral N at the outset of the study, related to the type of manure under consideration. The aim of this study was therefore to quantify the N mineralised from the organic fraction of farm manures under field conditions and to better understand the factors controlling the rate of N mineralisation. Additionally, the study aimed to derive simple predictive relationships to describe the rate of manure N mineralisation which could be used to improve predictions of crop available N supply and nitrate leaching losses following farm manure applications to land.

Materials and methods

Experimental sites

The study was undertaken from 1996 to 2001 at two experimental sites in the UK with contrasting climatic conditions (Table 1). Site 1 at Gleadthorpe in Nottinghamshire (SK593700), was on a loamy sand textured soil with a previous history of arable cropping and a low annual rainfall (650 mm). Site 2 at North Wyke in Devon (SX659983) was on a coarse sandy loam textured soil, also with a previous history of arable cropping, but in a high annual rainfall area (1000 mm).

Treatments

In spring 1996, nine manures (two cattle slurries, a pig slurry, two cattle FYMs, two pig FYMs, one broiler litter and one layer manure) were collected from commercial farms across England and Wales. The manures were selected to provide contrasting C:organic N ratios. Between 5 and 15 tonnes of solid manure and 25m^3 of slurry were collected.

The manures were 'stripped' of their ammonium-N content by cycles of wetting and drying over a period of 8 weeks, scaling up the approach used by Chadwick *et al*. (2000). This was achieved by spreading the solid manures on plastic sheets at depths of between 5 and 15 cm, and after initial drying, the manures were re-wetted and turned periodically to encourage ammonia volatilisation. The slurries were held in lagoons constructed using straw bales and butyl liners. The slurries were allowed to settle and the supernatant (which contained high concentrations of ammonium-N) removed by pumping until only *c*.50 cm of semi-solid manure remained. The dry matter of the supernatant was tested to ensure that solid manure organic matter was not being lost; in all cases the dry matter of the discarded liquid was less than 1%. The semi-solid material was then spread out onto plastic sheets and treated in the same manner as the solid manures to encourage ammonia losses. The procedures were undertaken as quickly as practically possible to minimise organic N release during the 'stripping' process. The 'stripping' techniques were effective at reducing the readily available N content (mineral N plus uric acid N) of the cattle, pig and poultry manures to < 5%, <10% and < 10% of the manure total N content, respectively.

The nine ‘stripped’ manures were then applied by hand to the experimental sites, together with an untreated control (no manure application), at rates equivalent to 15-100 t/ha dry solids, depending on the manure type, except for cattle slurry 1 where there was insufficient dry solids left after the stripping process and only 7-8 t/ha was applied. The high application rates were to ensure enough organic N was applied to be able to detect differences in mineralisation rates between treatments. At both sites, there were three replicates of each treatment in a randomised block design, with plots 3m x 10m in size. Following land application, the manures were left on the surface for 48 hours to further encourage ammonia volatilisation losses, before being intimately mixed with the soil using a spading machine and rotavator prior to drilling with perennial ryegrass (*Lolium perenne*) in June 1996. No white clover was present on the plots at either site. Triplicate samples of the applied manures were analysed post-spreading for dry matter, nitrate-N, ammonium-N, uric-acid N (poultry manure only), total N and organic carbon (Anon, 1986), from which the final total N loadings were calculated (Table 2). The C:organic N ratios of the applied manures (Table 2) were in broad agreement with those of a survey of over 800 farm manures (Table 3; Defra, 2003), except for the broiler litter, which was higher than the survey results.

No N fertiliser was applied to the plots, however phosphate and potash fertiliser dressings were based on the site soil analysis results and applied at recommended rates, after making allowance for the phosphate and potash supplied in the farm manure applications (Anon., 2010). Both sites were cultivated and re-seeded during the course of the experiment to determine whether cultivation would stimulate further manure organic N release; this was carried out in July 1997 at site 1 (Gleadthorpe) and August 1999 at site 2 (North Wyke).

Grass yield and nitrogen uptake

Grass cuts were taken from site 1 (Gleadthorpe) in July 1996, September 1996, December 1996, April 1997, June 1997, June 1998, July 1999, June 2000 and July 2001, and at site 2 (North Wyke) in September 1996, November 1996, May 1997, July 1997, October 1997, June 1998, August 1999, July 2000 and June 2001. At each cut, yield measurements were made and grass samples analysed for total N and dry matter (Anon., 1986) so that crop N uptakes could be calculated.

Nitrate leaching losses

Porous ceramic cups were installed at 90cm depth at site 1 (Gleadthorpe) and 60cm depth at site 2 (North Wyke) on all plots (4 cups per plot) to measure nitrate-N leaching losses (Webster *et al.,* 1993). Samples of soil water were collected after every 50 mm of drainage or two weeks, whichever occurred sooner, throughout winters 1996/97, 1997/98, 1998/99, 1999/2000 and 2000/01, and analysed for nitrate-N. Total nitrate-N leaching losses (kg/ha) were calculated using nitrate-N concentrations from the porous cup samples and estimates of drainage from the Irriguide water balance model (Bailey & Spackman, 1996). Ammonium-N in the leachate samples was not measured as it is generally rapidly nitrified to nitrate-N.

Estimation of manure organic N mineralisation

The amount of N mineralised from the applied organic manures was estimated by subtracting the sum of grass N uptakes + N leached on the untreated control from the sum of N uptakes + N leached on the manure treatments. This calculation assumed loss of N via denitrification or volatilisation was minimal, as nitrous oxide emissions from applied farm manures are typically <1% of the total manure N applied (IPCC, 2006) and manures were incorporated into the soil thereby minimising further ammonia volatilisation losses. The initial readily available N content of the applied manures (i.e. that not removed by the ‘stripping’ process, equivalent to <10% of the total N content) was subtracted from the manure N uptake values, assuming 100% efficiency of the readily available N applied.

Soil temperatures at 10 cm depth were monitored continuously at each site and soil moisture contents measured gravimetrically each month during the experiment. Manure N mineralisation rates were then related to thermal time, calculated as the cumulative day degrees (CDD) above 5 degrees after application, so that organic N ‘decay’ curves could be determined for each manure type.

Statistical analysis

Analysis of variance (ANOVA) was used to determine whether differences in plant N uptake, N leaching and calculated manure N mineralisation between the different manure types were statistically significant at $P<0.05$ (Genstat version 12; VSN International Ltd, 2010). The relationship between manure N mineralisation (expressed as a percentage of the manure organic N applied) and CDD was explored using regression analysis, and the slopes of the relationships derived for the different manure types compared using 95% confidence intervals.

Results

Grass N uptake

During the 12 months following land application (June 1996 to June 1997), grass N uptake net of the untreated control at Gleadthorpe (Site 1) was greatest on the pig slurry treatment at 265 kg/ha N and smallest on the pig FYM-2 treatment at 23 kg/ha N ($P<0.05$). This equated to 46% and 3% of the organic N applied, respectively (Figure 1). Following cultivation of the site in July 1997, grass N uptake on all the manure treatments was greater than on the untreated control in June 1998, July 1999 and June 2000 ($P<0.05$). Grass N uptake post cultivation was equivalent to a mean of 5% (range 3-7%) of the organic N applied (Figure 1). However, by July 2001, grass N uptake on the manure treatments was the same ($P>0.05$) as on the untreated control, indicating that manure organic N mineralisation had effectively stopped (had dropped to un-detectable levels, as measured by grass N uptake) in the fifth year after application.

Grass N uptake net of the untreated control at North Wyke (Site 2) was generally higher than at Gleadthorpe, especially in the first 3 months after application. The greatest ($P<0.05$) N uptake was measured on the pig slurry and layer manure treatments (68% and 61% of organic N applied, respectively), and lowest on the cattle slurry-1 treatment (9% of organic N applied); Figure 2). N uptake data from the grass cuts taken in October 1997, June 1998 and August 1999 were not different from the untreated control ($P>0.05$), indicating that mineralisation of the manure organic N had effectively ceased *c.*13 months after the initial application (Figure 2). Moreover, following cultivation in August 1999, grass N uptakes in July 2000 and June 2001 on the manure treatments were not different from those on the untreated control ($P>0.05$), indicating that cultivation had not stimulated further manure organic N release.

Nitrate leaching losses

In the first winter following application (1996/97), rainfall at Gleadthorpe and North Wyke was 85% and 75% of the long-term average (Table 4), respectively. The low rainfall, coupled with large moisture deficits created by the grass cover in the dry summer of 1996, meant that drainage did not begin at both sites until early December 1996. Nitrate-N leaching losses at Gleadthorpe were less than 1% of organic N applied on the cattle / pig FYM and cattle slurry treatments, and *c.*3% on the pig slurry, broiler litter and layer manure treatments (Table 5). At North Wyke, leaching losses were comparable to those at

Gleadthorpe, except on the pig slurry treatment where losses were equivalent to 10% of the applied organic N (Table 5).

In subsequent years (1997/98 and 1998/99), relatively wet summers meant that drainage began in late October/early November at both sites. In the second winter (1997/98), nitrate-N leaching losses at Gleadthorpe increased to 10% and 12 % of the applied organic N on the cattle FYM -1 and cattle slurry -1 treatments, respectively (Table 5). At North Wyke, leaching losses on all the manure treatments were less than 1% of the organic N applied and not significantly different from the untreated control (P>0.05). This is in agreement with the grass N uptake results, confirming that mineralisation of the manure organic N had effectively ceased at this site *c.*13 months after the initial manure application. Drainage volumes were greatest in winter 2000/01, reflecting overwinter rainfall *c.*50% and *c.*40% greater than the long-term average at Gleadthorpe and North Wyke, respectively (Table 4). However, in winters 1998/99, 1999/2000 and 2000/01, nitrate leaching losses on the manure treatments at both sites were similar to those on the untreated control (P>0.05), indicating that released organic N was not contributing to the N leached.

Manure organic N mineralisation

The estimated amount of N mineralised from the applied organic manures, expressed as a percentage of the organic N applied was related to thermal time after application (expressed as cumulative day degrees above 5°C; CDD). At Gleadthorpe, the relationship (Figure 3a) could be divided into three phases: phase 1 (up to *c.*1300 CDD) when grass growth was limited by the dry summer weather after the site was established (total rainfall 89 mm in 3 months), phase 2 when plant N uptake proceeded rapidly (*c.*1300-2200 CDD) during autumn 1996 and spring/summer 1997, and Phase 3 (>*c.*2200 CDD) when mineralisation had slowed. At North Wyke, the better grass growing conditions immediately after the ryegrass established (total rainfall 122 mm in 3 months) meant that crop uptake of the mineralised N was less limited by drought (Figure 3b), but after *c*. 2300 CDD, mineralisation of the applied manures had effectively ceased at the site.

Based on visual inspection of the data in Figure 3a and b, two phases of mineralisation were identified: a rapid phase which continued up to 2300 CDD, and a slower phase when thermal time exceeded 2300 CDD.

Relationship between manure organic N mineralisation and thermal time up to 2300 CDD

Across both sites, the greatest amounts of N mineralisation up to 2300 CDD were from the pig slurry (52% and 67% of organic N applied at Gleadthorpe and North Wyke, respectively) and layer manure (36% and 60%, of organic N applied at Gleadthorpe and North Wyke, respectively) treatments. The lowest amounts were from the cattle FYM-2 and pig FYM-2 treatments at Gleadthorpe (4% of organic N applied for both treatments), and from the cattle slurry-2 treatment at North Wyke (10% of organic N applied). Up to 2300 CDD, manure organic N mineralisation was linearly related to thermal time ($P<0.01$ and $r^2 > 70\%$), but varied with manure type (Table 6). Comparison of 95% confidence intervals for the slope of each relationship showed that the relationships fell into 2 broad groups at each site (Figure 4a,b). The first group included pig slurry and layer manure which had a higher rate of mineralisation (0.014 - 0.028 % mineralised/CDD), compared with the second group which included cattle/pig FYM and cattle slurry that had lower rates of mineralisation (0.002-0.014 % mineralised/CDD). Broiler litter fell midway between these two groups (0.01-0.018 %mineralised/CDD).

The amounts of N mineralised by the two manure type groups (FYM/cattle slurry and pig slurry/poultry manure) were used to derive ‘standard’ organic N release functions. This was initially done for each site separately, as CDDs were different at the two sites. The broiler litter results were excluded from the relationships, because of their atypically high C:organic N ratio (at 15:1; Table 2). Again there were significant differences between the slopes of the two manure type groups (based on a comparison of the 95% confidence intervals), but not between the two sites (Table 7). Consequently, the results from the two sites were pooled in order to derive ‘generic’ organic N release functions for future modelling purposes (Figure 5). These were:

For pig slurry and poultry manure (C: organic N 9-12; mean = 10):

$$\text{\% organic N mineralised} = 0.022/\text{CDD up to 2300 CDD} \qquad (1)$$

For cattle/pig FYM and cattle slurry (C: organic N 10-21; mean = 14):

$$\text{\% organic N mineralised} = 0.0076/\text{CDD up to 2300 CDD} \qquad (2)$$

Relationship between manure organic N mineralisation and thermal time over 2300 CDD

At Gleadthorpe, mineralisation of the organic manures continued to occur, albeit at a much slower rate at CDD>2300. This may have been due to the stimulation of mineralisation following cultivations at *c*.2200 CDD. During this second phase, the amount of N mineralised (expressed as a percentage of the manure organic N applied) was again linearly related to thermal time ($P = 0.05$), with similar slopes for both manure type groups (Table 7). However, due to differences in N mineralisation rates during the first phase the initial starting value (i.e. the intercept) was higher for the pig slurry and layer manure group than the cattle/pig FYM and cattle slurry group. At North Wyke, mineralisation effectively ceased (was undetectable) at >2300 CDD for both manure type groups (Table 7), and was not stimulated by cultivation in August 1999.

As with the period up to *c*.2300 CDD, results from the two sites were combined. These were:

For cattle/pig FYM and cattle slurry:

$$\text{\% organic N mineralised} = 0.0004/\text{CDD} \quad (3)$$

For pig slurry and poultry manure:

$$\text{\% organic N mineralised} = 0.0001/\text{CDD} \quad (4)$$

Overall, differences in net N mineralisation between the two manure type groups largely occurred in the period up to 2300 CDD. Combining equations 1-4 gave the following ‘generic’ functions, suitable for modelling purposes:

Prediction of % organic N mineralised from cattle/pig FYM and cattle slurry:

$$\text{\% organic N mineralised} = (0.0076*2300)+[(\text{CDD}-2300)*0.0004)] \quad (5)$$

Prediction of % organic N mineralised from pig slurry & poultry manure:

$$\text{\% organic N mineralised} = (0.0076*2300)+[(\text{CDD}-2300)*0.0004)] \quad (6)$$

Discussion

The crop available N supply from livestock manure applications is not limited to its readily available (mineral) N content. Mineralisation of the organic N fraction, both in the year of application and subsequent seasons can also contribute significant amounts of N, particularly where manures are repeatedly applied to the same field (Whitmore & Schröder, 1996; Schröder *et al.*, 2007). Indeed, Schröder *et al.* (2007) showed that grass dry matter yields responded positively to both current manure applications (cattle slurry and FYM) and applications made in previous seasons (4 annual applications), whereas mineral fertiliser N only affected yields in the year of application. Both the mineral and organic N supply from the applied manures was considered by Schröder *et al.* (2007), whereas the work described here assessed the N contribution derived almost entirely from the organic fraction of the applied manures, i.e. from mineralisation.

There has been much research effort into understanding, quantifying and modelling the factors which affect the mineralisation of soil organic nitrogen derived from a variety of sources (Jarvis *et al*., 1996). As a microbially mediated process it is highly dependent on soil temperature and moisture (Whitmore, 2007; Watts *et al*., 2010), as well as the composition of the applied materials (e.g. C:N ratio, lignin content; Chadwick *et al*., 2000; Pu *et al.*, 2012). The amount of N released can also differ in response to soil texture, with greater protection of organic matter and consequently lower rates of mineralisation in clay soils (Hassink, 1994). A number of studies have used thermal time to predict N mineralisation. For example, Douglas & Rickman (1992) simulated crop residue decomposition as a function of thermal time and observed a rapid decomposition rate up to 1000 CDD which was related to the N content of the residue, followed by a slower phase at >1000 CDD, which was regulated by the lignin content of the crop residue. Clough *et al*. (1998) measured soil organic matter mineralisation rates on a range of grassland soils and found that mineralisation was linearly related to cumulative soil temperatures above 0°C. Similarly, Honeycutt & Potaro (1990) found that soil thermal units (CDD) were useful in predicting net mineralisation. The combination of a release curve approach and CDD data, although a relatively crude approach, is attractive in its simplicity and has been shown to improve the accuracy of predicting manure N availability (Castellanos & Pratt, 1981; Klausner *et al*., 1994).

In this study, manure organic N mineralisation was related to CDD (above 5°C) in two phases; an initial phase up to 2300 CDD (*c.*18 months under UK climatic conditions) where mineralisation proceeded at rates ranging between 0.005-0.027 %mineralised/CDD, and a slower phase at >2300 CDD, where rates were negligible at <0.001 %mineralised/CDD. There was no difference between soil types, both being light-textured, although net N mineralisation dropped to undetectable levels much earlier (after 18-24 months) on the slightly heavier textured soil in the high rainfall area (North Wyke), compared to the site in the low rainfall area and lighter textured soil (Gleadthorpe), where mineralisation of the manure organic N was detectable up to 4 years after application. Gil *et al.* (2010) also observed that mineralisation of compost applied to soil in a laboratory incubation study occurred in two phases, an initial rapid phase during the first year of application, where the relationship between %N mineralised and time was best described by an exponential function, and a slower phase in the second year which was described by a 'special model', with more parameters. They concluded that this suggested the organic N in the compost consisted of two fractions with different degrees of stability – labile organic N and resistant organic N. Schröder *et al.* (2007) in a field study also observed that the residual N effect of manure applications was greatest in the year of application and 'faded away' afterwards.

Schröder *et al*. (2007) found no clear distinction between the two contrasting manure types studied (cattle FYM and cattle slurry); however the C:organic N ratios of the manures were very similar (in the range 14.8-15.8). In this current study, the greater amount of N mineralised from the pig slurry and layer manure compared with the cattle slurry & cattle/pig FYMs was most likely a reflection of differences in the C:organic N ratios of the manure types. Pig slurry and layer manure had lower C:organic N ratios (range 9-12:1) than the cattle slurry and straw-based FYMs (range 10-21:1). Chadwick *et al.* (2000) also showed that the amount of N mineralised from a range of farm manures in a laboratory incubation study was inversely related to the C:organic N ratio of the manures ($P<0.01$; $r^2 = 0.63$). Similarly, Serna & Pomares (1991) demonstrated a significant relationship between animal manure C:N ratios and N mineralisation (r^2=-48%), and Floate (1970) showed a weak relationship between the C:N ratio of sheep faeces and N mineralised (r^2=-31%). Moreover, Eghball *et al.* (2002) estimated that mineralized organic N availability was highest in poultry/broiler manures (55%) and in lowest in dairy (21%) and composted (18%) manures in the first year of a laboratory incubation study. However, Castellanos & Pratt (1981) found no relationship between manure C:N ratios and N mineralised for a range of stored and fresh animal manures.

The results also clearly indicate the importance of taking into account mineralisation when calculating manure N efficiency coefficients, particularly where manures are repeatedly applied to the same field. For pig slurry and layer manure up to 70% of the organic N was mineralised, predominantly in the first 18 months after application, but continuing for up to 4 years on the lighter textured soil, compared with 10-30% mineralisation from the cattle slurry and cattle/pig FYMs. However, although the manure organic N mineralisation was greatest for the pig slurry, giving rise to higher manure N efficiencies in the first 18 months, the longer-term residual effect of a manure application is considered to be greater for FYM, as at typical application rates (i.e. rates equivalent to 250 kg/ha total N) this supplies more organic N than slurry (Schröder *et al*., 2005; Van Dijk & ten Berge, 2009). Importantly, 100% manure organic N mineralisation was never achieved, with the remaining manure organic N most likely contributing to the very stable soil organic matter (humus) pool.

Conclusions

Mineralisation of the organic N fraction of farm manures, both in the year of application and subsequent seasons can contribute significant amounts of crop available N, which should be taken into account in fertiliser recommendations in order to reduce losses to the wider environment. The amount of N mineralised was seen to be dependent on the manure C:organic N ratio, with greater mineralisation at ratios ranging from 9-12:1 (pig slurry and poultry manures) compared to cattle slurries and straw-based FYMs, with C:organic N ratios in the range 10-21:1. Temperature after application was also important and simple relationships were derived for each of these groups of manures for the amount of N mineralised and thermal time. The relationships derived provide a useful tool for predicting both the amount and timing of manure N release, with important implications for both crop N uptake and leaching risk. Indeed the functions have been recently incorporated into a decision support tool (MANNER-*NPK*; Nicholson *et al.*, 2013), which quantifies manure crop available nutrient supply, and is designed to support the better use of manure nutrients to enable both savings in fertilisers and a reduction in environmental impacts.

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Table 1. Soil type, cropping and average annual rainfall.

Site	Topsoil texture (% clay)	Average annual rainfall (mm)[1]	Topsoil total N (%)	Topsoil organic matter (%)	Topsoil C: N ratio
Gleadthorpe	Loamy sand (9%)	650	0.04	1.7	25:1
North Wyke	Sandy loam (18%)	1000	0.08	1.8	13:1

[1] 30 year average

Table 2. Total N loadings and C: organic N ratios of the manures applied at each field site; standard errors shown in brackets.

Treatment	Total N loading (kg/ha)		C: organic N ratio	
	Gleadthorpe	North Wyke	Gleadthorpe	North Wyke
Cattle FYM 1	526 (80)	632 (51)	21.2 (2.3)	19.5 (4.4)
Cattle FYM 2	901 (44)	848 (36)	11.0 (0.3)	11.0 (0.3)
Pig FYM 1	863 (98)	1031 (37)	14.4 (2.6)	12.2 (1.0)
Pig FYM 2	794 (89)	861 (100)	9.8 (2.0)	8.1 (0.2)
Cattle slurry 1	172 (15)	364 (6)	13.0 (1.2)	10.3 (0.3)
Cattle slurry 2	676 (52)	724 (8)	14.3 (2.1)	13.3 (0.7)
Pig slurry	577 (28)	543 (36)	11.8 (0.8)	11.3 (5.0)
Broiler litter	674 (46)	364 (19)	15.4 (0.6)	14.8 (1.8)
Layer manure	659 (67)	638 (46)	8.8 (0.8)	9.7 (1.2)

Table 3. Carbon and nitrogen composition of a range of farm manures. Average data taken from the Defra Manure Analysis Database (Defra, 2003); standard errors shown in brackets.

Manure	Sample number[1]	Dry matter (%)	Organic C (% dm)	Organic N (% dm)[2]	C: organic N[3]
Cattle FYM	230-263	23 (0.5)	33 (0.4)	2.3 (0.1)	14.3
Cattle slurry	89-179	8.5 (0.2)	34 (0.4)	2.5 (0.1)	13.6
Pig FYM	35-39	26 (1.4)	32 (1.1)	2.3 (0.2)	13.9
Pig slurry	17-75	3.7 (0.5)	33 (1.9)	3.5 (0.3)	9.4
Poultry litter[4]	28-40	60 (2.1)	33 (1.0)	3.4 (0.2)	9.7
Layer manure	87-95	35 (1.1)	28 (0.5)	2.9 (0.2)	9.7

[1] Not all samples collected were analysed for organic C; [2] Organic N was calculated by subtracting the average readily available N content (ammonium-N + nitrate-N + uric acid N) from the average total N content; [3] Calculated from the reported average C and organic N contents. [4] A combination of broiler and turkey litters

Table 4. Overwinter rainfall (1st September to 31st March) and drainage (mm).

Site	Gleadthorpe		North Wyke	
	Rainfall	Drainage	Rainfall	Drainage
Average Annual	364	-	756	-
96/97	316	85	584	173
97/98	322	148	540	189
98/99	407	124	646	423
99/00	311	123	740	593
00/01	522	278	1078	688

Table 5. Total nitrate-N leached in winters 1996/97 and 1997/98 expressed as a % of the organic N applied.

Treatment	1996/97		1997/98
	GT	NW	GT
Cattle FYM1	0.8	0.3	10.4
Cattle FYM2	0.1	0.3	0.7
Pig FYM1	1.1	2.6	0.7
Pig FYM2	0.7	0.3	0.1
Cattle slurry 1	0.1	0.2	13.0
Cattle slurry 2	0.2	0.3	0.6
Pig slurry	2.7	10.0	1.1
Broiler litter	2.5	0.3	3.0
Layer manure	3.4	2.4	4.6

Note: N leaching on the treated plots was identical to the untreated control at North Wyke in 1997/98 and at both sites in 1998/99, 1999/00 and 2000/01.

Table 6. Relationship between manure organic N mineralisation (% organic N applied) and thermal time (up to 2300 CDD). GT = Gleadthorpe, NW = North Wyke

Treatment	r^2		*P*		Slope		95% CI*	
	GT	NW	GT	NW	GT	NW	GT	NW
Cattle FYM1	0.85	0.81	<0.001	0.002	0.005	0.014	0.0013	0.0055
Cattle FYM2	0.76	0.86	<0.001	0.001	0.002	0.010	0.0004	0.0031
Pig FYM1	0.77	0.89	0.001	0.001	0.007	0.014	0.0028	0.0038
Pig FYM2	0.73	0.89	0.008	0.001	0.002	0.009	0.0012	0.0024
Cattle slurry 1	0.87	0.87	<0.001	0.001	0.007	0.012	0.0022	0.0036
Cattle slurry 2	0.90	0.90	<0.001	<0.001	0.005	0.004	0.0011	0.0012
Pig slurry	0.88	0.95	<0.001	<0.001	0.021	0.028	0.0051	0.0051
Broiler litter	0.93	0.95	<0.001	<0.001	0.010	0.018	0.0017	0.0031
Layer manure	0.85	0.97	<0.001	<0.001	0.014	0.027	0.0039	0.0034

*95% confidence interval (CI) = standard deviation x t; where t = 2.571 for Gleadthorpe (5 df) and 2.776 for North Wyke (4 df)

Table 7. Relationships between manure organic N mineralisation (% organic N applied) and thermal time (CDD above 5 °C) at Gleadthorpe (GT) and North Wyke (NW).

Treatment	r^2		*P*		Slope		95% CI	
	GT	NW	GT	NW	GT	NW	GT	NW
Relationship up to 2300 CDD:								
FYM & cattle slurry	0.89	0.86	<0.001	<0.001	0.005	0.01	0.001	0.003
Pig slurry & layer manure	0.87	0.96	<0.001	<0.001	0.017	0.027	0.004	0.004
Relationship > 2300 CDD:								
FYM & cattle slurry	0.67	0.55	0.05	0.10 (NS)	0.0011	0.0002	13.1	26.3
Pig slurry & layer manure	0.68	0.11	0.05	0.31 (NS)	0.0011	0.0001	44.1	64.1

Figure 1

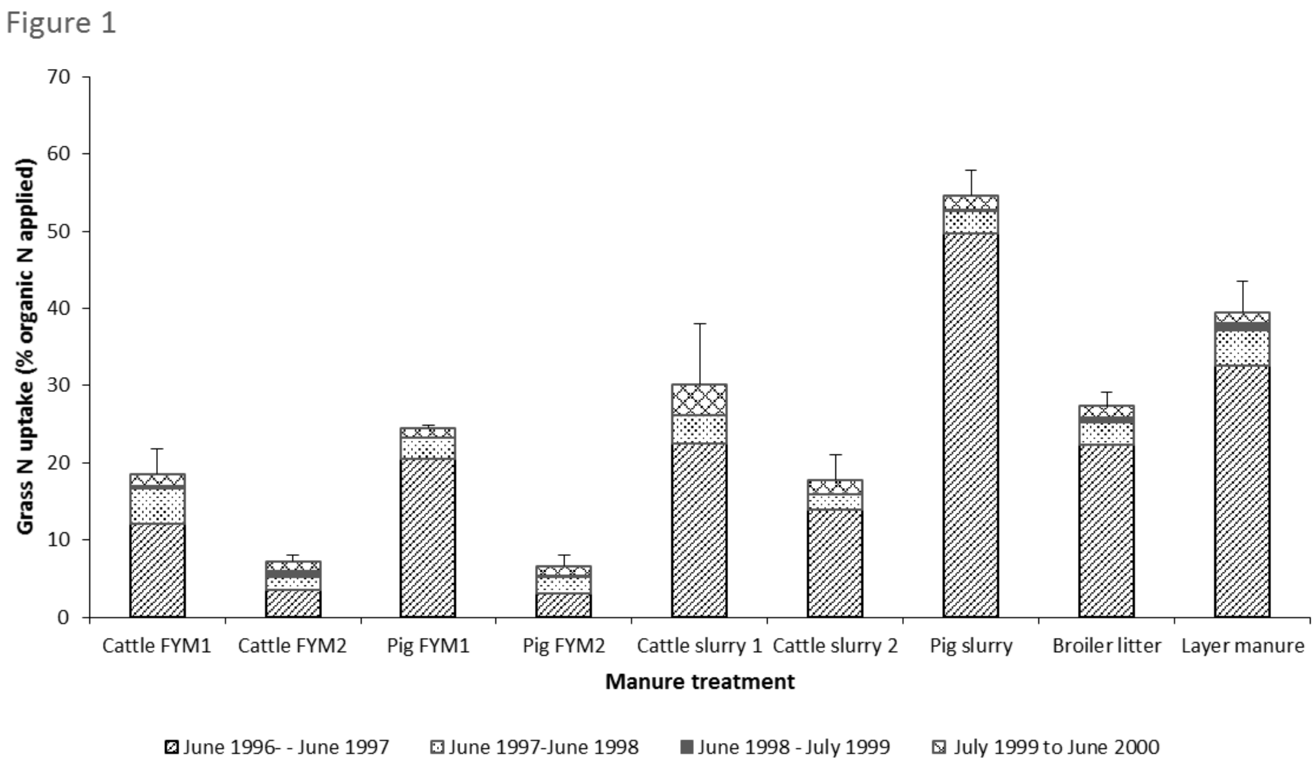
Figure 1
Grass N uptake (% organic N applied)
0
10
20
30
40
50
60
70
Cattle FYM1
Cattle FYM2
Pig FYM1
Pig FYM2
Cattle slurry 1
Cattle slurry 2
Pig slurry
Broiler litter
Layer manure
Manure treatment
June 1996- - June 1997
June 1997-June 1998
June 1998 - July 1999
July 1999 to June 2000

Figure 2

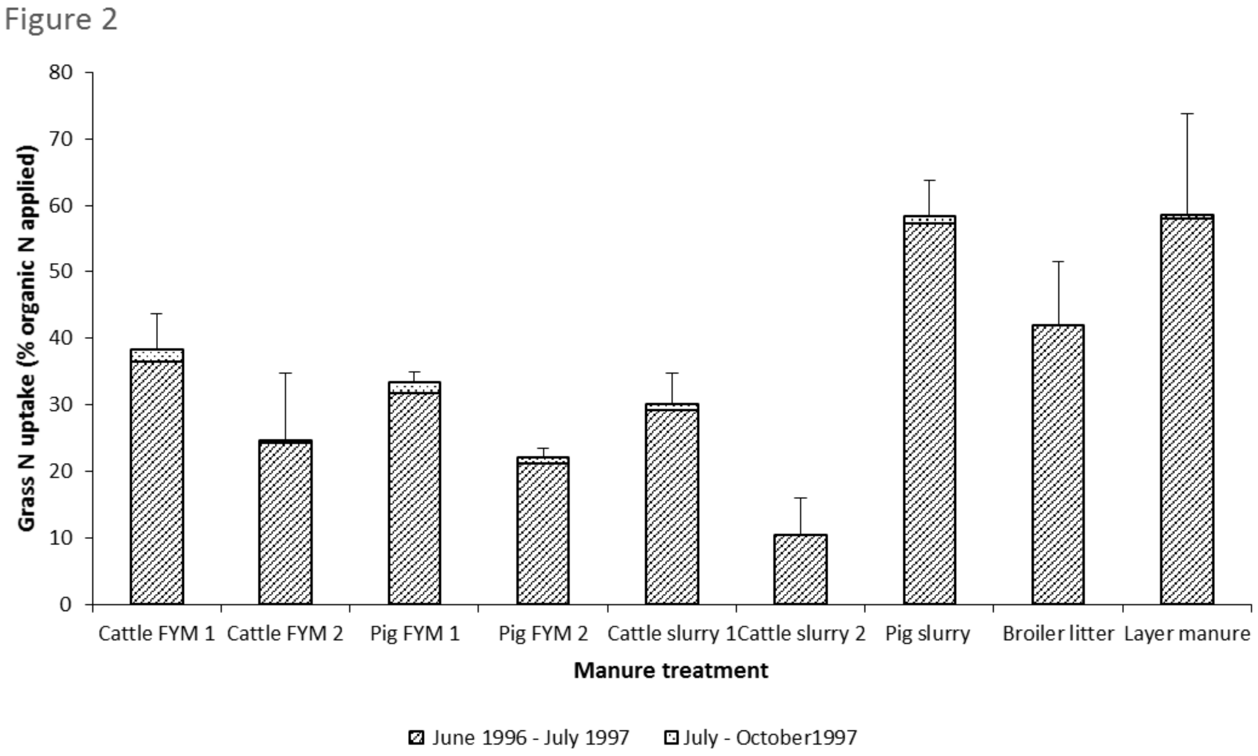
Figure 2
Grass N uptake (% organic N applied)
80
70
60
50
40
30
20
10
0
Cattle FYM 1
Cattle FYM 2
Pig FYM 1
Pig FYM 2
Cattle slurry 1
Cattle slurry 2
Pig slurry
Broiler litter
Layer manure
Manure treatment
▨ June 1996 - July 1997
▨ July - October1997

Figure 3a

Fig. 3a

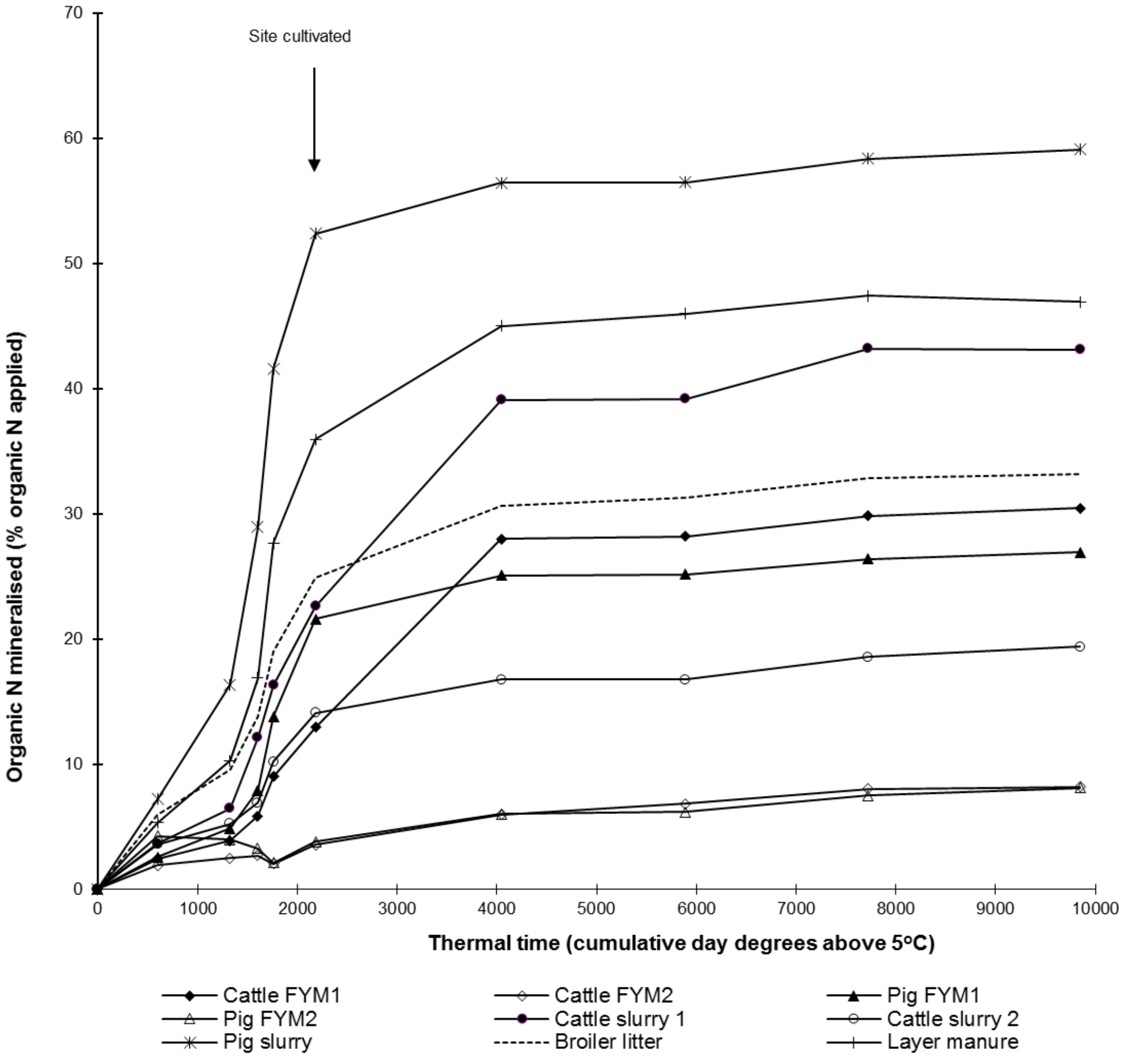

Figure 3b

Fig. 3b.

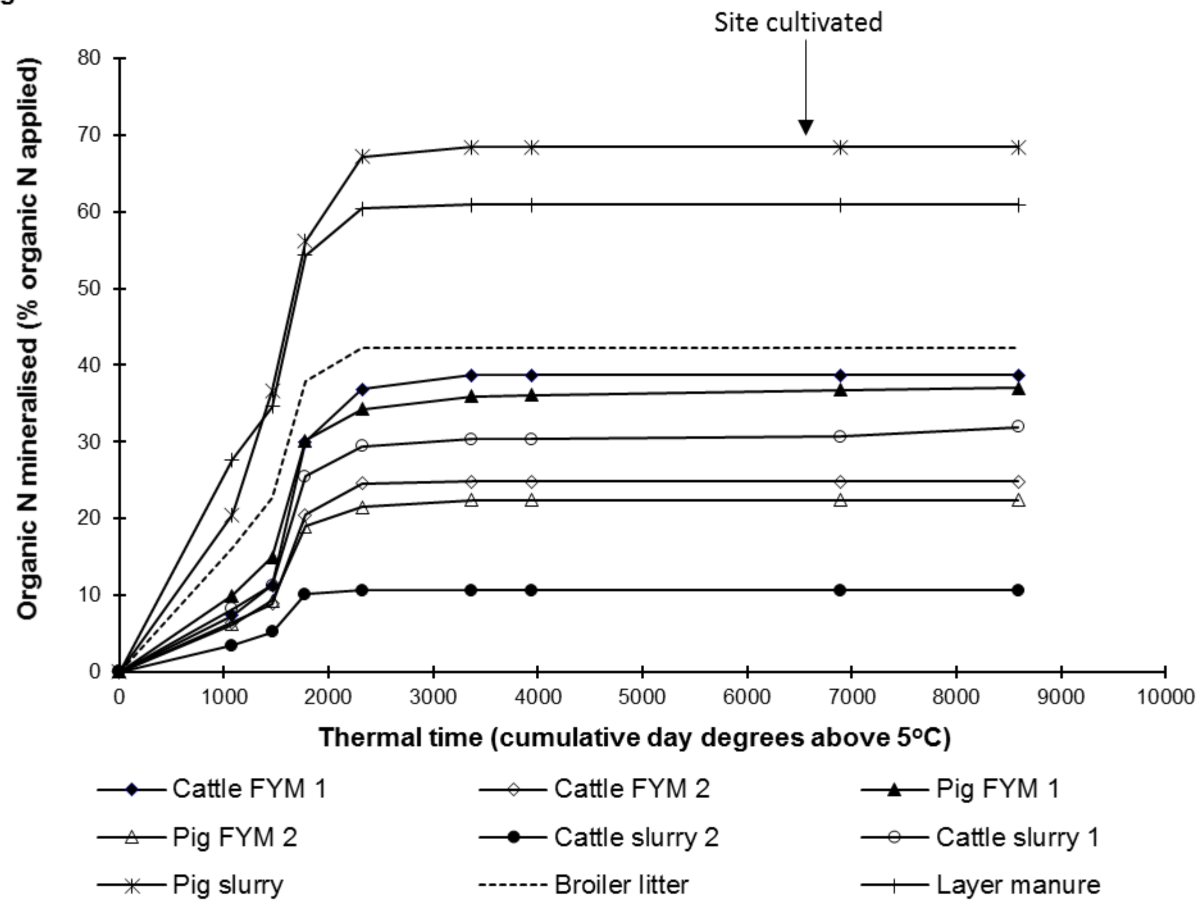

Figure 4a.

Fig. 4a

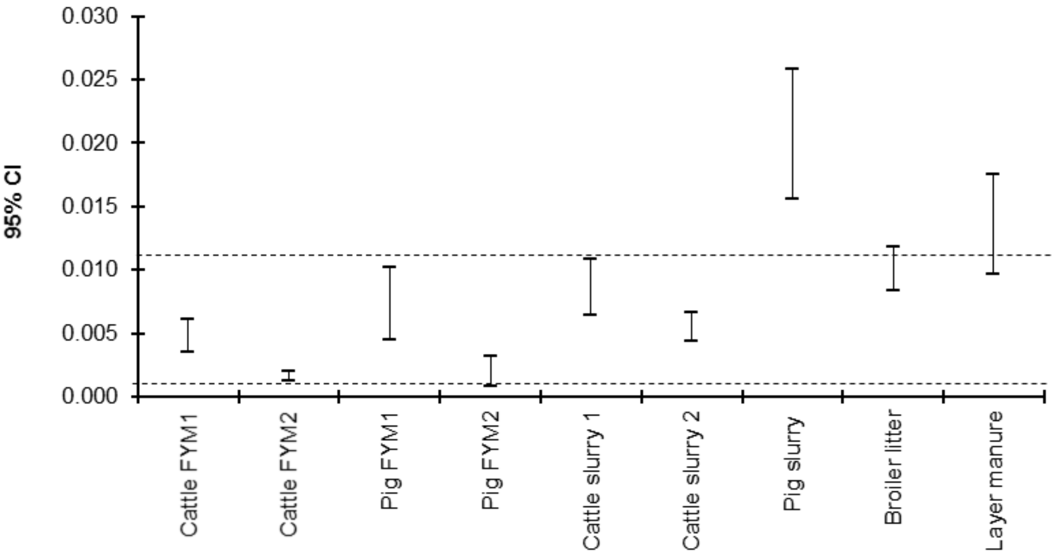

Figure 4b.

Fig. 4b

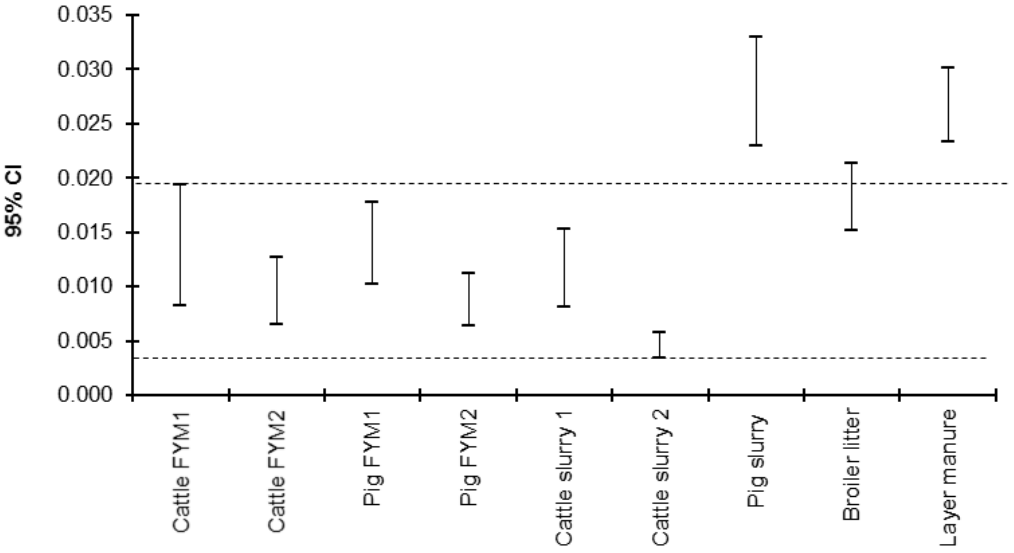

Figure 5.

Fig. 5.