

## Mineralization of organic nitrogen from farm manure applications

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1 **Mineralisation of organic nitrogen from farm manure applications**

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9 **Running Title:** Manure organic N mineralisation

10 **Abstract**

11 This study aimed to quantify the amount of nitrogen (N) mineralised from the organic  
12 fraction of farm manures under field conditions. Nine different farm manures were stripped  
13 of their ammonium-N content prior to soil incorporation and establishment of ryegrass at  
14 two sites in England. Grass N uptake and nitrate-N leaching were measured for five  
15 consecutive seasons and compared with an untreated control, with the sum of N uptake +  
16 leaching (net of the control) used as an estimate of the amount of organic N mineralised  
17 from the applied manures. The amount mineralised was related to thermal time (cumulative  
18 day degrees above 5°C – CDD), with two distinct phases – an initial phase up to 2300 CDD  
19 (c.18 months under UK climatic conditions) where mineralisation proceeded at rates ranging  
20 between 0.005-0.027 %mineralised/CDD, and a slower phase at >2300 CDD, where rates  
21 were negligible at <0.001 %mineralised/CDD. There was no difference between soil types,  
22 both being light-textured (<20% clay), but there were differences between manure types  
23 depending on the manure C: organic N ratios. For pig slurry and layer manure (C:organic N  
24 = 9-12:1) up to 70% of the organic N was mineralised, compared to 10-30% mineralisation

25 from the cattle slurry and straw based FYMs (C:organic N = 10-21:1).The relationships  
26 derived provide a useful tool for predicting both the amount and timing of manure N release,  
27 with important implications for both crop N uptake and leaching risk.

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

### 30 **Introduction**

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

45

46 A key requirement of the Nitrate Vulnerable Zones Action Programme (NVZ AP) in  
47 England (SI, 2008) is for farmers to formally take into account the crop available N supply  
48 from livestock manure applications. This requires the use of manure N use efficiency (NUE)

49 coefficients (or fertiliser replacement values) to calculate how much of the total N content  
50 of a livestock manure applied to their land will be available for the following crop. In  
51 England and Wales, these range from 10% for pig and cattle farmyard manures to 50% for  
52 pig slurry, with poultry manures predicted to have an NUE of 30% (Anon., 2013), based  
53 largely on analyses of their readily available N content with some allowance for losses  
54 (mainly via nitrate leaching and ammonia volatilisation). In a review of manure N use  
55 efficiency throughout Europe, Webb *et al.* (2013) reported that NUEs are commonly based  
56 on the N estimated to be available during the first growing season only and that most  
57 countries predict short-term mineralisation using a simple N model of the annual relative  
58 decomposition rates of manure organic N. They concluded that whilst longer term effects of  
59 organic N mineralisation are important and should be considered, this does not yet occur in  
60 the majority of EU Member States. .

61

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

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

80

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

91

## 92 **Materials and methods**

### 93 *Experimental sites*

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

98 coarse sandy loam textured soil, also with a previous history of arable cropping, but in a  
99 high annual rainfall area (1000 mm).

#### 100 *Treatments*

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

105

106 The manures were ‘stripped’ of their ammonium-N content by cycles of wetting and drying  
107 over a period of 8 weeks, scaling up the approach used by Chadwick *et al.* (2000). This was  
108 achieved by spreading the solid manures on plastic sheets at depths of between 5 and 15 cm,  
109 and after initial drying, the manures were re-wetted and turned periodically to encourage  
110 ammonia volatilisation. The slurries were held in lagoons constructed using straw bales and  
111 butyl liners. The slurries were allowed to settle and the supernatant (which contained high  
112 concentrations of ammonium-N) removed by pumping until only *c.*50 cm of semi-solid  
113 manure remained. The dry matter of the supernatant was tested to ensure that solid manure  
114 organic matter was not being lost; in all cases the dry matter of the discarded liquid was less  
115 than 1%. The semi-solid material was then spread out onto plastic sheets and treated in the  
116 same manner as the solid manures to encourage ammonia losses. The procedures were  
117 undertaken as quickly as practically possible to minimise organic N release during the  
118 ‘stripping’ process. The ‘stripping’ techniques were effective at reducing the readily  
119 available N content (mineral N plus uric acid N) of the cattle, pig and poultry manures to <  
120 5%, <10% and < 10% of the manure total N content, respectively.

121

122 The nine 'stripped' manures were then applied by hand to the experimental sites, together  
123 with an untreated control (no manure application), at rates equivalent to 15-100 t/ha dry  
124 solids, depending on the manure type, except for cattle slurry 1 where there was insufficient  
125 dry solids left after the stripping process and only 7-8 t/ha was applied. The high application  
126 rates were to ensure enough organic N was applied to be able to detect differences in  
127 mineralisation rates between treatments. At both sites, there were three replicates of each  
128 treatment in a randomised block design, with plots 3m x 10m in size. Following land  
129 application, the manures were left on the surface for 48 hours to further encourage ammonia  
130 volatilisation losses, before being intimately mixed with the soil using a spading machine  
131 and rotavator prior to drilling with perennial ryegrass (*Lolium perenne*) in June 1996. No  
132 white clover was present on the plots at either site. Triplicate samples of the applied manures  
133 were analysed post-spreading for dry matter, nitrate-N, ammonium-N, uric-acid N (poultry  
134 manure only), total N and organic carbon (Anon, 1986), from which the final total N  
135 loadings were calculated (Table 2). The C:organic N ratios of the applied manures (Table 2)  
136 were in broad agreement with those of a survey of over 800 farm manures (Table 3; Defra,  
137 2003), except for the broiler litter, which was higher than the survey results.

138 No N fertiliser was applied to the plots, however phosphate and potash fertiliser dressings  
139 were based on the site soil analysis results and applied at recommended rates, after making  
140 allowance for the phosphate and potash supplied in the farm manure applications (Anon.,  
141 2010). Both sites were cultivated and re-seeded during the course of the experiment to  
142 determine whether cultivation would stimulate further manure organic N release; this was  
143 carried out in July 1997 at site 1 (Gleadthorpe) and August 1999 at site 2 (North Wyke).

144 *Grass yield and nitrogen uptake*

145 Grass cuts were taken from site 1 (Gleadthorpe) in July 1996, September 1996, December  
146 1996, April 1997, June 1997, June 1998, July 1999, June 2000 and July 2001, and at site 2  
147 (North Wyke) in September 1996, November 1996, May 1997, July 1997, October 1997,  
148 June 1998, August 1999, July 2000 and June 2001. At each cut, yield measurements were  
149 made and grass samples analysed for total N and dry matter (Anon., 1986) so that crop N  
150 uptakes could be calculated.

#### 151 *Nitrate leaching losses*

152 Porous ceramic cups were installed at 90cm depth at site 1 (Gleadthorpe) and 60cm depth at  
153 site 2 (North Wyke) on all plots (4 cups per plot) to measure nitrate-N leaching losses  
154 (Webster *et al.*, 1993). Samples of soil water were collected after every 50 mm of drainage  
155 or two weeks, whichever occurred sooner, throughout winters 1996/97, 1997/98, 1998/99,  
156 1999/2000 and 2000/01, and analysed for nitrate-N. Total nitrate-N leaching losses (kg/ha)  
157 were calculated using nitrate-N concentrations from the porous cup samples and estimates  
158 of drainage from the Irriguide water balance model (Bailey & Spackman, 1996).  
159 Ammonium-N in the leachate samples was not measured as it is generally rapidly nitrified  
160 to nitrate-N.

#### 161 *Estimation of manure organic N mineralisation*

162 The amount of N mineralised from the applied organic manures was estimated by  
163 subtracting the sum of grass N uptakes + N leached on the untreated control from the sum  
164 of N uptakes + N leached on the manure treatments. This calculation assumed loss of N via  
165 denitrification or volatilisation was minimal, as nitrous oxide emissions from applied farm  
166 manures are typically <1% of the total manure N applied (IPCC, 2006) and manures were  
167 incorporated into the soil thereby minimising further ammonia volatilisation losses. The  
168 initial readily available N content of the applied manures (i.e. that not removed by the



169 'stripping' process, equivalent to <10% of the total N content) was subtracted from the  
170 manure N uptake values, assuming 100% efficiency of the readily available N applied.

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

#### 176 *Statistical analysis*

177 Analysis of variance (ANOVA) was used to determine whether differences in plant N  
178 uptake, N leaching and calculated manure N mineralisation between the different manure  
179 types were statistically significant at  $P<0.05$  (Genstat version 12; VSN International Ltd,  
180 2010). The relationship between manure N mineralisation (expressed as a percentage of the  
181 manure organic N applied) and CDD was explored using regression analysis, and the slopes  
182 of the relationships derived for the different manure types compared using 95% confidence  
183 intervals.

## 184 **Results**

185

#### 186 *Grass N uptake*

187 During the 12 months following land application (June 1996 to June 1997), grass N uptake  
188 net of the untreated control at Gleadthorpe (Site 1) was greatest on the pig slurry treatment  
189 at 265 kg/ha N and smallest on the pig FYM-2 treatment at 23 kg/ha N ( $P<0.05$ ). This  
190 equated to 46% and 3% of the organic N applied, respectively (Figure 1). Following  
191 cultivation of the site in July 1997, grass N uptake on all the manure treatments was greater  
192 than on the untreated control in June 1998, July 1999 and June 2000 ( $P<0.05$ ). Grass N

193 uptake post cultivation was equivalent to a mean of 5% (range 3-7%) of the organic N  
194 applied (Figure 1). However, by July 2001, grass N uptake on the manure treatments was  
195 the same ( $P>0.05$ ) as on the untreated control, indicating that manure organic N  
196 mineralisation had effectively stopped (had dropped to un-detectable levels, as measured by  
197 grass N uptake) in the fifth year after application.

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

#### 209 *Nitrate leaching losses*

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

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

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

### 232 *Manure organic N mineralisation*

233 The estimated amount of N mineralised from the applied organic manures, expressed as a  
234 percentage of the organic N applied was related to thermal time after application (expressed  
235 as cumulative day degrees above 5°C; CDD). At Gleadthorpe, the relationship (Figure 3a)  
236 could be divided into three phases: phase 1 (up to *c.*1300 CDD) when grass growth was  
237 limited by the dry summer weather after the site was established (total rainfall 89 mm in 3  
238 months), phase 2 when plant N uptake proceeded rapidly (*c.*1300-2200 CDD) during autumn  
239 1996 and spring/summer 1997, and Phase 3 ( $>c.$ 2200 CDD) when mineralisation had  
240 slowed. At North Wyke, the better grass growing conditions immediately after the ryegrass

241 established (total rainfall 122 mm in 3 months) meant that crop uptake of the mineralised N  
242 was less limited by drought (Figure 3b), but after *c.* 2300 CDD, mineralisation of the applied  
243 manures had effectively ceased at the site.

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

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

248 Across both sites, the greatest amounts of N mineralisation up to 2300 CDD were from the  
249 pig slurry (52% and 67% of organic N applied at Gleadthorpe and North Wyke, respectively)  
250 and layer manure (36% and 60%, of organic N applied at Gleadthorpe and North Wyke,  
251 respectively) treatments. The lowest amounts were from the cattle FYM-2 and pig FYM-2  
252 treatments at Gleadthorpe (4% of organic N applied for both treatments), and from the cattle  
253 slurry-2 treatment at North Wyke (10% of organic N applied). Up to 2300 CDD, manure  
254 organic N mineralisation was linearly related to thermal time ( $P < 0.01$  and  $r^2 > 70\%$ ), but  
255 varied with manure type (Table 6). Comparison of 95% confidence intervals for the slope of  
256 each relationship showed that the relationships fell into 2 broad groups at each site (Figure  
257 4a,b). The first group included pig slurry and layer manure which had a higher rate of  
258 mineralisation (0.014 - 0.028 % mineralised/CDD), compared with the second group which  
259 included cattle/pig FYM and cattle slurry that had lower rates of mineralisation (0.002-0.014  
260 % mineralised/CDD). Broiler litter fell midway between these two groups (0.01-0.018  
261 % mineralised/CDD).

262 The amounts of N mineralised by the two manure type groups (FYM/cattle slurry and pig  
263 slurry/poultry manure) were used to derive 'standard' organic N release functions. This was  
264 initially done for each site separately, as CDDs were different at the two sites. The broiler

265 litter results were excluded from the relationships, because of their atypically high C:organic  
266 N ratio (at 15:1; Table 2). Again there were significant differences between the slopes of the  
267 two manure type groups (based on a comparison of the 95% confidence intervals), but not  
268 between the two sites (Table 7). Consequently, the results from the two sites were pooled in  
269 order to derive 'generic' organic N release functions for future modelling purposes (Figure  
270 5). These were:

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

$$272 \quad \% \text{ organic N mineralised} = 0.022/\text{CDD up to 2300 CDD} \quad (1)$$

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

$$274 \quad \% \text{ organic N mineralised} = 0.0076/\text{CDD up to 2300 CDD} \quad (2)$$

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

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

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

287 For cattle/pig FYM and cattle slurry:

288           % organic N mineralised = 0.0004/CDD (3)

289 For pig slurry and poultry manure:

290           % organic N mineralised = 0.0001/CDD (4)

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

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

295           % organic N mineralised = (0.0076\*2300)+[(CDD-2300)\*0.0004] (5)

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

297           % organic N mineralised = (0.0076\*2300)+[(CDD-2300)\*0.0004] (6)

## 298 **Discussion**

299 The crop available N supply from livestock manure applications is not limited to its readily  
300 available (mineral) N content. Mineralisation of the organic N fraction, both in the year of  
301 application and subsequent seasons can also contribute significant amounts of N,  
302 particularly where manures are repeatedly applied to the same field (Whitmore & Schröder,  
303 1996; Schröder *et al.*, 2007). Indeed, Schröder *et al.* (2007) showed that grass dry matter  
304 yields responded positively to both current manure applications (cattle slurry and FYM) and  
305 applications made in previous seasons (4 annual applications), whereas mineral fertiliser N  
306 only affected yields in the year of application. Both the mineral and organic N supply from  
307 the applied manures was considered by Schröder *et al.* (2007), whereas the work described  
308 here assessed the N contribution derived almost entirely from the organic fraction of the  
309 applied manures, i.e. from mineralisation.

310 There has been much research effort into understanding, quantifying and modelling the  
311 factors which affect the mineralisation of soil organic nitrogen derived from a variety of  
312 sources (Jarvis *et al.*, 1996). As a microbially mediated process it is highly dependent on  
313 soil temperature and moisture (Whitmore, 2007; Watts *et al.*, 2010), as well as the  
314 composition of the applied materials (e.g. C:N ratio, lignin content; Chadwick *et al.*, 2000;  
315 Pu *et al.*, 2012). The amount of N released can also differ in response to soil texture, with  
316 greater protection of organic matter and consequently lower rates of mineralisation in clay  
317 soils (Hassink, 1994). A number of studies have used thermal time to predict N  
318 mineralisation. For example, Douglas & Rickman (1992) simulated crop residue  
319 decomposition as a function of thermal time and observed a rapid decomposition rate up to  
320 1000 CDD which was related to the N content of the residue, followed by a slower phase at  
321 >1000 CDD, which was regulated by the lignin content of the crop residue. Clough *et al.*  
322 (1998) measured soil organic matter mineralisation rates on a range of grassland soils and  
323 found that mineralisation was linearly related to cumulative soil temperatures above 0°C.  
324 Similarly, Honeycutt & Potaro (1990) found that soil thermal units (CDD) were useful in  
325 predicting net mineralisation. The combination of a release curve approach and CDD data,  
326 although a relatively crude approach, is attractive in its simplicity and has been shown to  
327 improve the accuracy of predicting manure N availability (Castellanos & Pratt, 1981;  
328 Klausner *et al.*, 1994).

329 In this study, manure organic N mineralisation was related to CDD (above 5°C) in two  
330 phases; an initial phase up to 2300 CDD (c.18 months under UK climatic conditions) where  
331 mineralisation proceeded at rates ranging between 0.005-0.027 %mineralised/CDD, and a  
332 slower phase at >2300 CDD, where rates were negligible at <0.001 %mineralised/CDD.  
333 There was no difference between soil types, both being light-textured, although net N  
334 mineralisation dropped to undetectable levels much earlier (after 18-24 months) on the

335 slightly heavier textured soil in the high rainfall area (North Wyke), compared to the site in  
336 the low rainfall area and lighter textured soil (Gleadthorpe), where mineralisation of the  
337 manure organic N was detectable up to 4 years after application. Gil *et al.* (2010) also  
338 observed that mineralisation of compost applied to soil in a laboratory incubation study  
339 occurred in two phases, an initial rapid phase during the first year of application, where the  
340 relationship between %N mineralised and time was best described by an exponential  
341 function, and a slower phase in the second year which was described by a 'special model',  
342 with more parameters. They concluded that this suggested the organic N in the compost  
343 consisted of two fractions with different degrees of stability – labile organic N and resistant  
344 organic N. Schröder *et al.* (2007) in a field study also observed that the residual N effect of  
345 manure applications was greatest in the year of application and 'faded away' afterwards.

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



360 in the first year of a laboratory incubation study. However, Castellanos & Pratt (1981) found  
361 no relationship between manure C:N ratios and N mineralised for a range of stored and fresh  
362 animal manures.

363 The results also clearly indicate the importance of taking into account mineralisation when  
364 calculating manure N efficiency coefficients, particularly where manures are repeatedly  
365 applied to the same field. For pig slurry and layer manure up to 70% of the organic N was  
366 mineralised, predominantly in the first 18 months after application, but continuing for up to  
367 4 years on the lighter textured soil, compared with 10-30% mineralisation from the cattle  
368 slurry and cattle/pig FYMs. However, although the manure organic N mineralisation was  
369 greatest for the pig slurry, giving rise to higher manure N efficiencies in the first 18 months,  
370 the longer-term residual effect of a manure application is considered to be greater for FYM,  
371 as at typical application rates (i.e. rates equivalent to 250 kg/ha total N) this supplies more  
372 organic N than slurry (Schröder *et al.*, 2005; Van Dijk & ten Berge, 2009). Importantly,  
373 100% manure organic N mineralisation was never achieved, with the remaining manure  
374 organic N most likely contributing to the very stable soil organic matter (humus) pool.

## 375 **Conclusions**

376 Mineralisation of the organic N fraction of farm manures, both in the year of application and  
377 subsequent seasons can contribute significant amounts of crop available N, which should be  
378 taken into account in fertiliser recommendations in order to reduce losses to the wider  
379 environment. The amount of N mineralised was seen to be dependent on the manure  
380 C:organic N ratio, with greater mineralisation at ratios ranging from 9-12:1 (pig slurry and  
381 poultry manures) compared to cattle slurries and straw-based FYMs, with C:organic N ratios  
382 in the range 10-21:1. Temperature after application was also important and simple  
383 relationships were derived for each of these groups of manures for the amount of N

384 mineralised and thermal time. The relationships derived provide a useful tool for predicting  
385 both the amount and timing of manure N release, with important implications for both crop  
386 N uptake and leaching risk. Indeed the functions have been recently incorporated into a  
387 decision support tool (MANNER-NPK; Nicholson *et al.*, 2013), which quantifies manure  
388 crop available nutrient supply, and is designed to support the better use of manure nutrients  
389 to enable both savings in fertilisers and a reduction in environmental impacts.

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508 two manure groups up to 2300 CDD.

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

Site	Topsoil texture (% clay)	Average annual rainfall (mm) <sup>1</sup>	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

517 <sup>1</sup>30 year average

518

519 Table 2. Total N loadings and C: organic N ratios of the manures applied at each field site;  
 520 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)

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523

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

Manure	Sample number <sup>1</sup>	Dry matter (%)	Organic C (% dm)	Organic N (% dm) <sup>2</sup>	C: organic N <sup>3</sup>
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 <sup>4</sup>	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

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

530

531 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

532

533

534 Table 5. Total nitrate-N leached in winters 1996/97 and 1997/98 expressed as a % of the  
 535 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

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

538

539 Table 6. Relationship between manure organic N mineralisation (% organic N applied) and  
 540 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

541 \*95% confidence interval (CI) = standard deviation x t; where t = 2.571 for Gleadthorpe (5  
 542 df) and 2.776 for North Wyke (4 df)

543

544

545 Table 7. Relationships between manure organic N mineralisation (% organic N applied)  
 546 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

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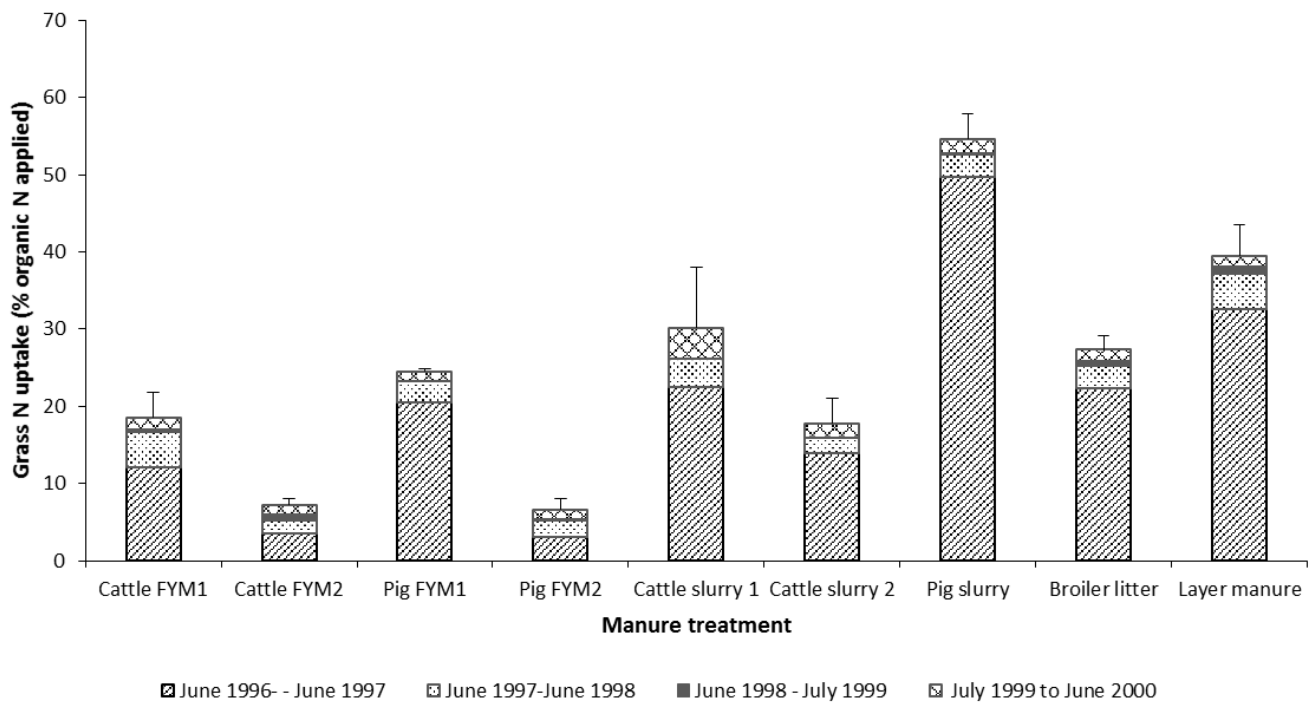
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Figure 1



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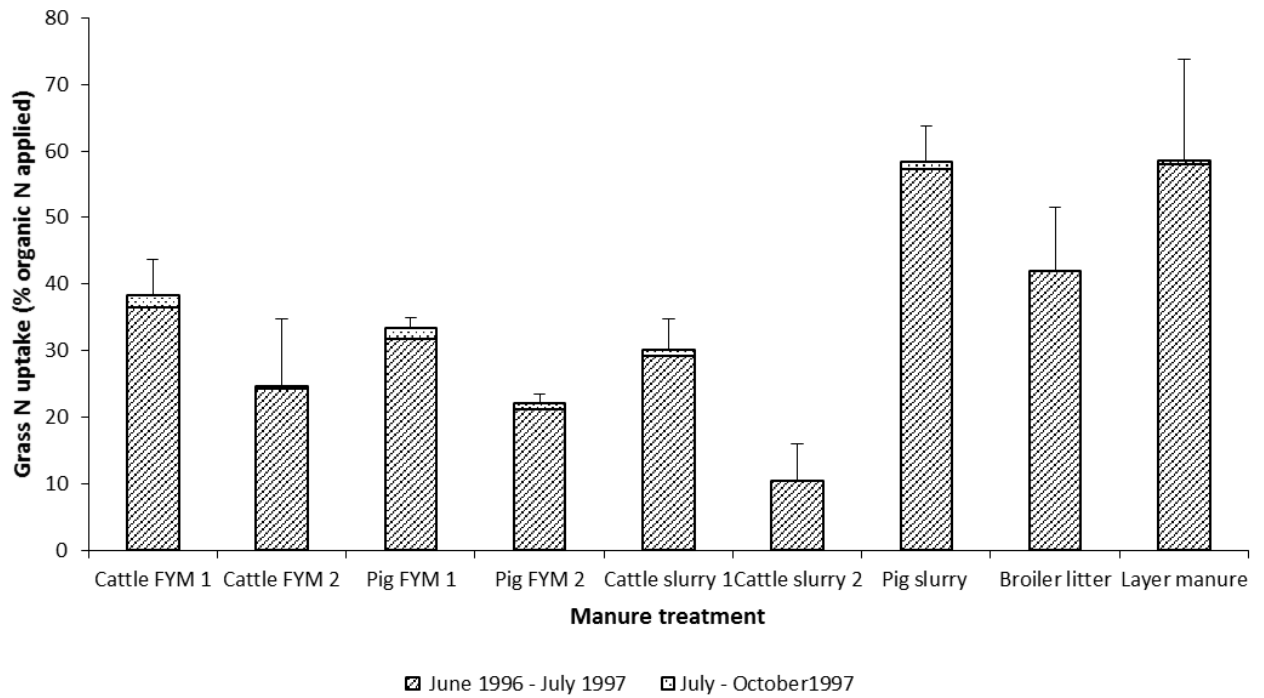


555 Figure 2

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Figure 2

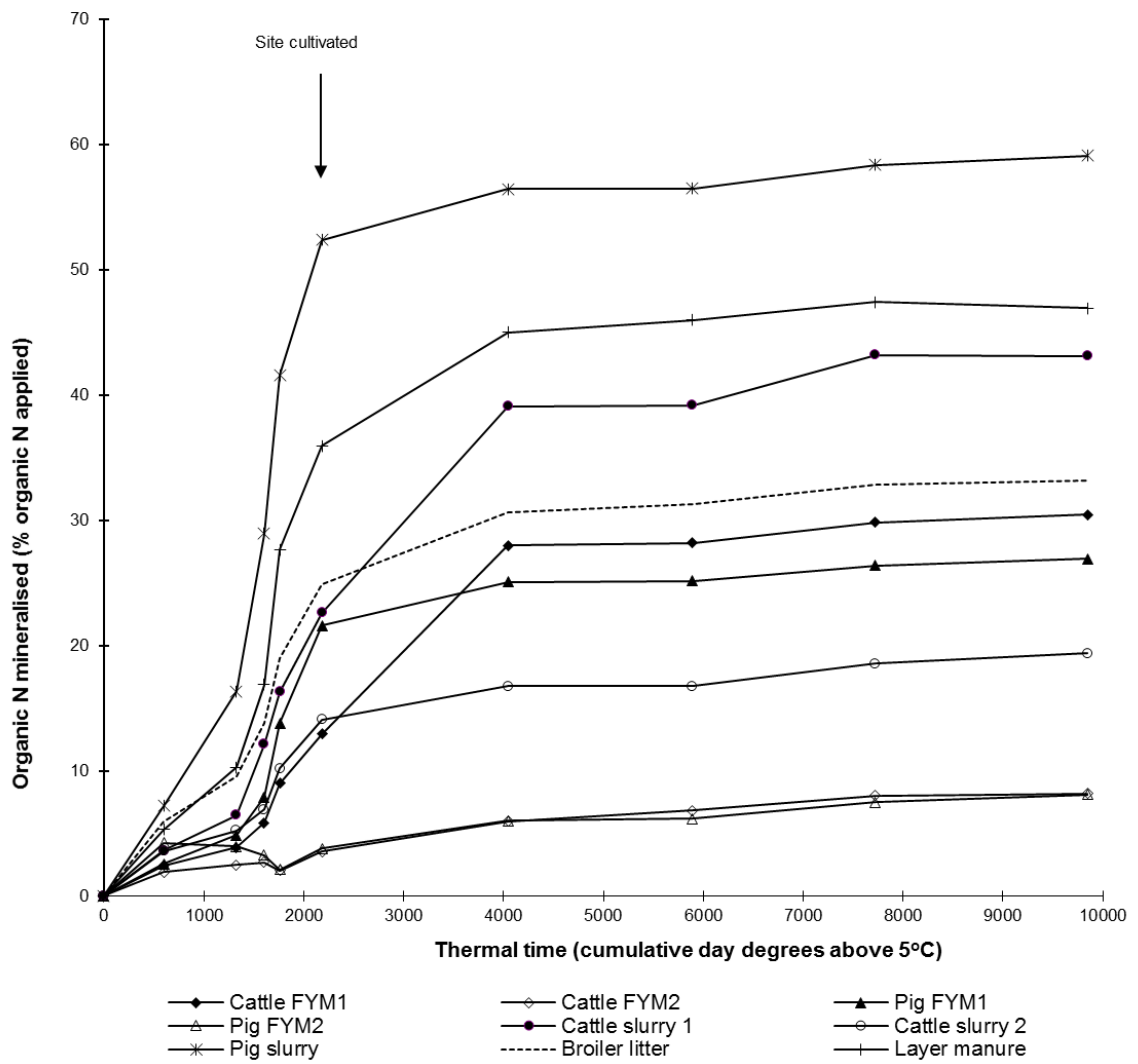


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Fig. 3a



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Fig. 3b.

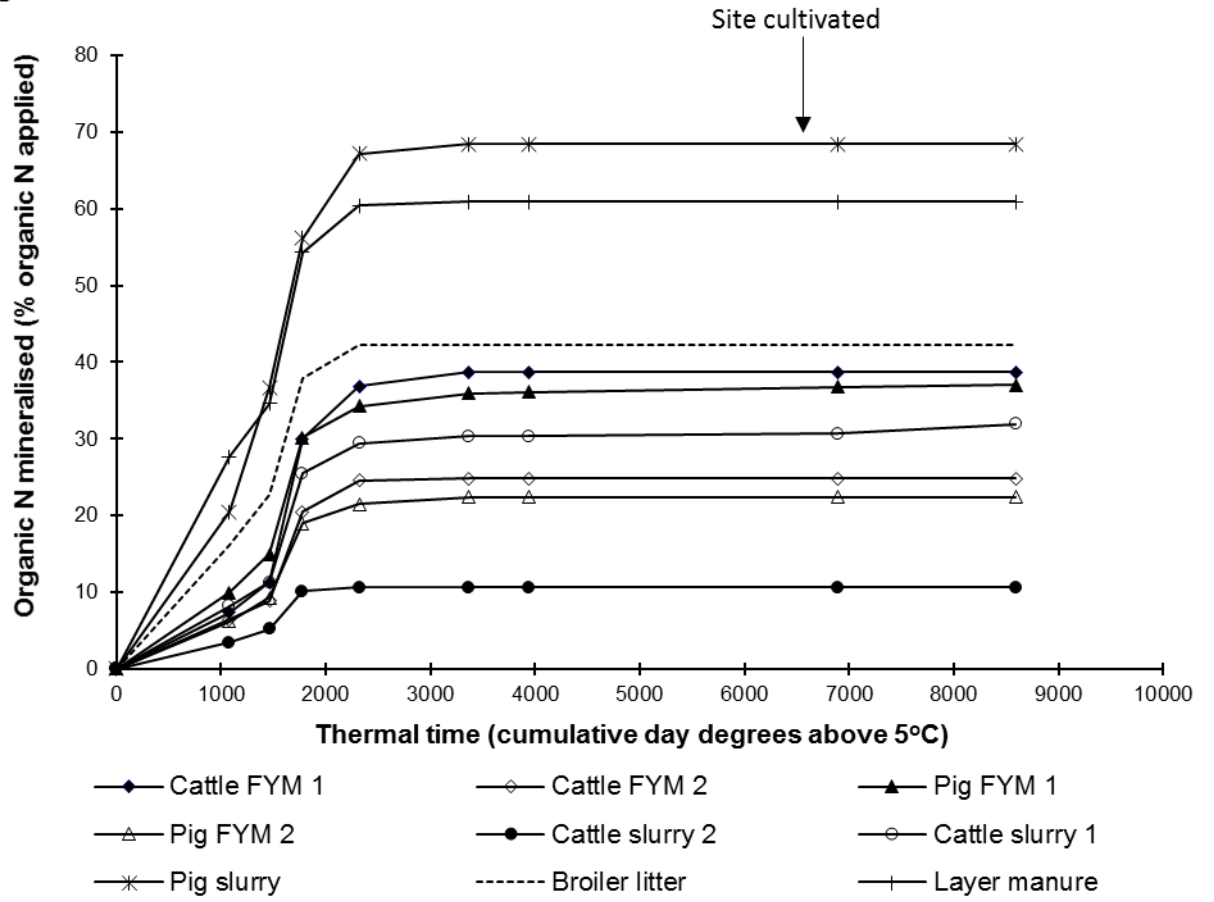
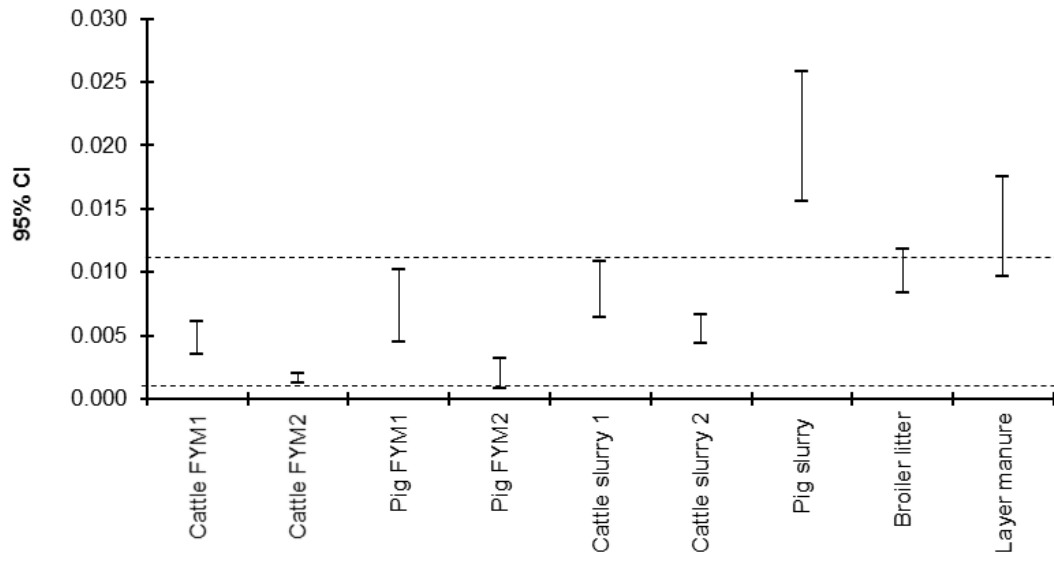


Fig. 4a



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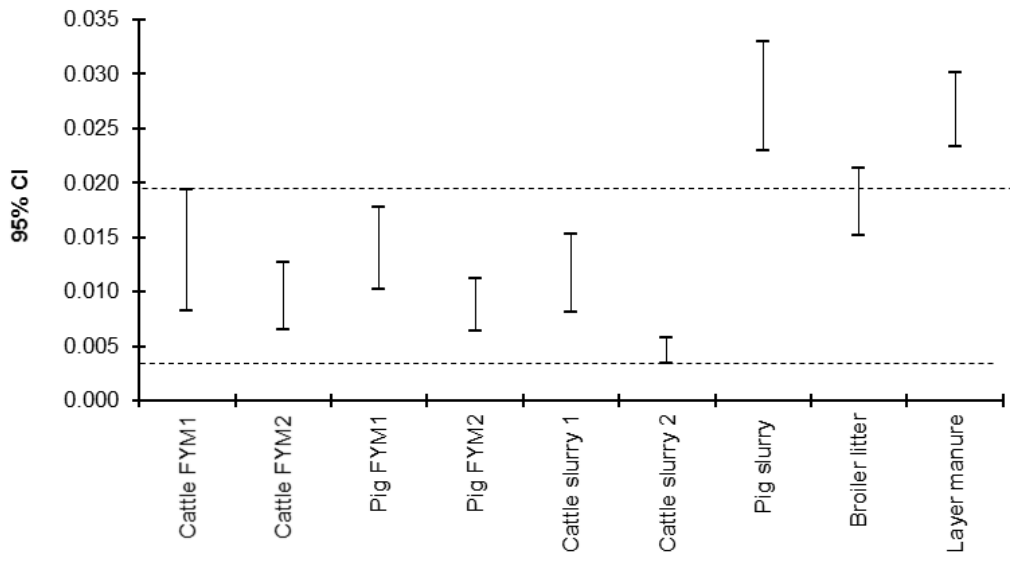
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569 Figure 4b.

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**Fig. 4b**

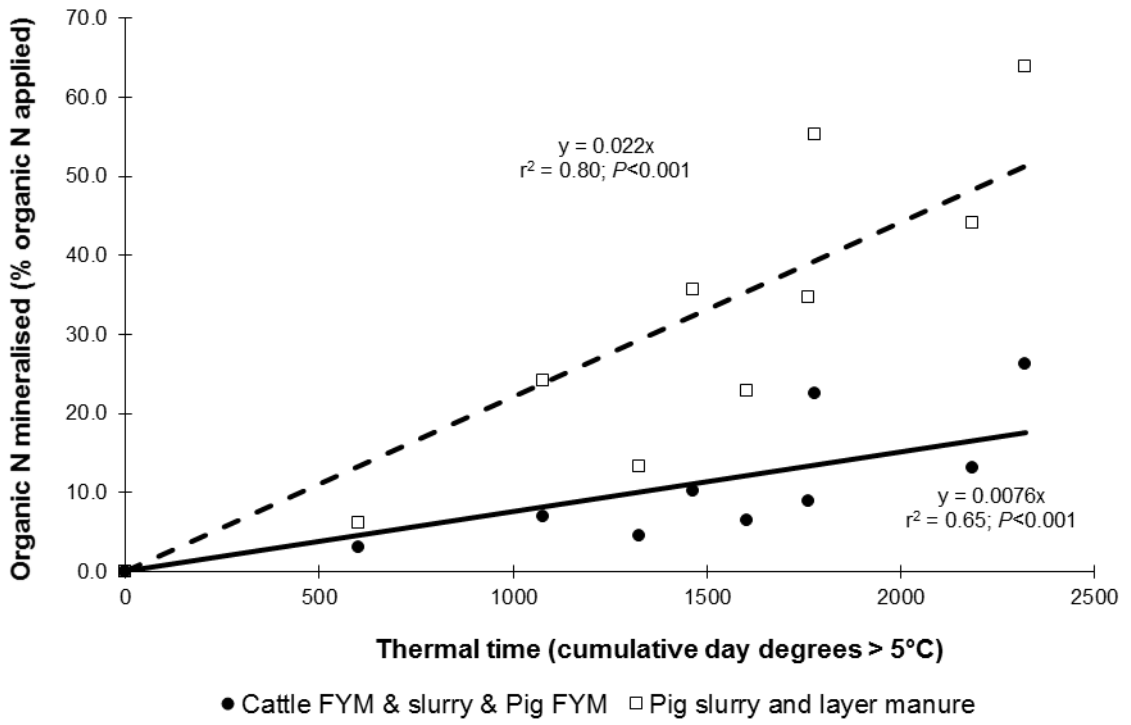


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573 Figure 5.

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Fig. 5.



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