Organic manure and crop organic carbon returns – effects on soil quality: SOIL-*QC*

Final report for Defra Project SP0530

Prepared by:
Anne Bhogal[a], Brian J. Chambers[a],
Andy P. Whitmore[b] & Iain Young[c]

[a]ADAS Gleadthorpe, Meden Vale,
Mansfield, Notts. NG20 9PF
[b]Rothamsted Research, Harpenden, Herts.
AL5 2JQ
[c]previously: SIMBIOS, University of Abertay,
Dundee, Scotland, DD1 1HG

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1. Executive summary

The overall objective of this project was to develop an improved understanding of the processes and linkages through which organic carbon (OC) additions influence soil bio-physical and physico-chemical properties. Seven established field experimental sites (previous Defra projects SP0501 and SP0504) with a history of repeated livestock manure additions (4 sites) or crop residue returns in response to differential rates of fertiliser nitrogen (N) application (3 sites) were used in this project. An important aspect of the study was to establish whether previously measured changes in soil properties in response to livestock manure additions were a result of *recent* OC additions or *historic* OC inputs accumulated over the long-term.

A range of soil bio-physical and physico-chemical properties were measured at the seven SOIL-*QC* experimental sites on contrasting soil types throughout England. Additionally, at the four organic material sites, green compost and paper crumble additions were introduced as new treatments in 2004. Plots at these sites were also split and livestock manure additions withheld for 2 years from one half of each plot ('historic' treatment), with the other half receiving manure annually ('recent' treatment). The rate of change in soil organic carbon (SOC) levels and effect of different organic material and crop residue management scenarios on SOC was evaluated through carbon turnover modelling, using the ROTH-C carbon model.

The main findings are summarised below:

- The OC inputs (up to 100 tC/ha applied over 14-28 years) changed a *large number* of soil properties relative to the untreated control (e.g. soil carbon storage, plant available water capacity, porosity and density, strength, N supply, cation exchange capacity, microbial biomass size). Overall, OC inputs in the form of livestock manures (farmyard manure-FYM, slurry, broiler litter) had the greatest influence on measured soil processes and properties. In comparison, there were relatively few changes resulting from crop residue OC inputs. Soil chemical (e.g. SOC, light fraction OC, extractable P, K, Mg) and biological (e.g. microbial biomass, fungal biomass, potentially mineralisable N) properties were the most responsive to OC additions, but a large number of soil physical properties (e.g. shear strength, aggregate stability, infiltration rates, plough resistance etc.) were un-affected. Compost and paper crumble had only been applied at the organic material experimental sites for 2-3 years prior to sampling, and therefore had relatively low OC loading rates and associated small effects on soil properties.

- Small (10-17% above the untreated control) but consistent *increases* in soil water retention from the application of livestock manures, and to a lesser extent compost (3-11% above the untreated control) and paper crumble (4-14% above the untreated control) were seen across the full range of water potentials (from field capacity to permanent wilting point), particularly on the sandy soils at Gleadthorpe (6% clay) and Harper Adams (12% clay). Water held between 0.05 and 2 bar tension is considered to be the easily available water capacity (EAWC) to plants and was on average 72% of the total plant AWC measured at all sites (range: 52-86% across all sites). The measured increases in water retention, particularly the EAWC, can have a significant impact on crop yields, water use and consequently farm economics, particularly on low AWC sandy soils where vegetables are grown. The estimated 10% increase in total plant AWC (following 50t/ha OC addition; estimated from the relationship between AWC and OC inputs measured

- The organic material additions (i.e. livestock manure, compost, paper crumble) were characterised according to their carbon composition (total OC, lignin, cellulose and dissolved OC). The lignin fraction is considered to be 'stable' and the cellulose and dissolved OC pools more 'readily decomposable'. Green compost had the greatest amount of stable OC (*c.*80% of TOC in the lignin pool), followed by solid livestock manures (*c.*30% OC in lignin pool) and paper crumble (*c.*20% OC in lignin pool).

- The increase in topsoil SOC measured in 2008 following 14-16 years of annual livestock manure additions and 24-30 years of differential crop residue returns accounted for *c.*31% of total livestock manure OC inputs and *c.*20% of total crop residue inputs to the soil. This indicates that 70-80% of total OC inputs had been oxidised and lost from the topsoil as carbon dioxide to the atmosphere, with the retention of stable OC in the topsoil greater for more 'resistant' C sources i.e. livestock manures compared with crop residues.

- Measured SOC levels at each of the seven sites were compared with predictions of C turnover generated using the ROTH-C model. The model gave good predictions of changes in SOC at the crop residue sites, using the default assumptions within ROTH-C, but over-estimated topsoil OC retention at the organic manure experimental sites. Here, characterisation of the organic material additions according to their carbon composition (i.e. lignin-resistant and cellulose-easily decomposable C) proved particularly valuable in improving ROTH-C model predictions of soil C turnover, using the *measured* lignin and cellulose concentrations to adjust the ratios of easily decomposable to resistant OC in the model. This is an important advance in our understanding of soil C turnover and long-term SOC storage where organic materials are recycled to agricultural land.

- The improvements in soil quality and functioning measured following repeated livestock manure additions persisted for at least 2 years following the cessation of applications. Overall, it was the total accumulated livestock manure OC load that had the greatest influence on soil properties and functioning, regardless of whether the livestock manure OC was 'fresh' (i.e. recently applied) or 'historic' (over 2 years old, i.e. OC remaining following 2 years of withholding manure additions), which was the case for 12 out of the 15 relationships. Clearly, the beneficial effects of livestock manure OC additions (i.e. increased SOC, AWC, porosity, N supply, strength and microbial biomass and decreased bulk density) are likely to persist in soils for several (many) years after applications have ceased. The only exceptions to this general rule were shown by soil light fraction OC, fungal biomass and extractable K levels. These findings are in contrast to the hypothesis of Loveland *et al*. (2001) who suggested that the 'active' or 'fresh' components of SOC were probably more important in controlling changes in soil properties, rather than the accumulated 'stable' SOC pool.

2. Introduction

Soil organic carbon (SOC) levels and turnover rates are intimately linked to soil properties that are important in the maintenance of soil quality and fertility, and sustainable crop production. However, because of the wide range of inter-linkages, it is difficult to distinguish the various processes and mechanisms through which SOC affects soil quality and fertility, associated crop productivity and environmental impacts. Arable cultivation is generally associated with declining SOC levels (Alison, 1973), with substantial decreases in SOM status observed following the ploughing out of grassland (Johnson & Prince, 1994). Between 1980 and 1994, soil organic carbon levels in arable/ley-arable soils in England and Wales decreased by an average of 6 g/kg, from *c.*34 g/kg *to c.*28 g/kg (Webb *et al.,* 2001). This has implications for the capacity of soils to store C, supply water and nutrients, and also their ability to resist erosion. Maintaining (and enhancing) SOC levels is a key component of “Safeguarding our Soils - A Strategy for England” (Defra, 2009), and SOC has been chosen as the headline indicator for soil health in the UK “Sustainable Farming and Food Strategy” (Anon, 2006). Farm manure applications and crop residues recycle *c.*5 and 15 million tonnes of OC to UK soils each year, respectively. Together with other organic amendments (e.g. green compost, paper crumble), these additions represent a potentially valuable means of replenishing SOC levels, that could confer benefits to soil bio-physical and physico-chemical properties, as well as supplying increasingly valuable plant available nutrients. A number of studies have shown decreased soil bulk density and increased water holding capacity, porosity, aggregation and biological activity following the application of farm manures (Rose, 1990, Schjonning *et al.,* 1994; Haynes & Naidu, 1998). Likewise, the return of OC in crop residues following the long-term application of inorganic nitrogen (N) fertiliser has been reported to increase soil aggregation, porosity, infiltration and water holding capacity (Schjonning *et al.,* 1994; Munkholm *et al.,* 2002); as well as biological activity and mineralisation rates (Haynes & Naidu, 1998; Rasmussen *et al*., 1998). Notably, these international studies have tended to focus on a single site or form of OC input and measured a limited set of soil properties.

Previous measurements at the established field experimental sites in England used in this project[1], with a history of repeated livestock manure additions or differential crop residue addition rates (in response to fertiliser N addition), demonstrated measurable improvements in a range of soil physical, chemical and biological properties in response to OC additions (Bhogal *et al.,* 2009). Building upon this previous research, this project, SOIL-*QC* aimed to develop an improved understanding of the processes and linkages through which OC additions influence soil bio-physical and physico-chemical properties. Additionally at the organic material sites, this project aimed to establish whether the measured changes were a result of ‘recent’ livestock manure OC additions or ‘historic’ OC inputs accumulated over the medium-term.

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[1] Also utilised in Defra projects SP0501 and SP0504.

3. Objectives

- **The overall objective of this project was to provide an improved understanding of the processes and linkages through which organic carbon (OC) additions influence soil bio-physical and physico-chemical properties (SOIL-*QC*).**

More specifically, the individual objectives of the project were:

i. To quantify the effects of repeated OC additions on soil bio-physical and physico-chemical properties.
ii. To quantify the effects of recent (within 2 years) and historic (older than 2 years) OC inputs on soil bio-physical and physico-chemical properties.
iii. To assess relationships between the rate and substrate quality of OC inputs and measured changes in soil properties and processes.
iv. To determine the effects of a range of OC inputs on crop yields and quality and farm economics.
v. To use the data generated to assess the rate of change in soil properties and evaluate the effect of different management scenarios through the modelling of C and N turnover.
vi. To assess the linkages and interactions through which OC additions effect soil quality and fertility, associated crop productivity and environmental impacts.

4. Methodology

4.1 Experimental sites and treatments

This study was undertaken from 2004 to 2009 at seven established experimental sites, previously utilised in Defra projects SP0501 and SP0504 from 1998-2002 (Defra, 2002 a;b). The sites had a history of repeated livestock manure (4 sites) or differential rates of crop residue additions in response to fertiliser N additions (3 sites; Table 1) and covered a range of soil textures (5-28% clay), with inherently 'low' SOC levels (6 sites ≤15 g/kg SOC; Bridgets 33g/kg SOC). Full details of the history of each of the sites prior to 1998 are given by Bhogal *et al.,* (2009). Briefly, differential rates of fertiliser N addition commenced in 1984 at sites 1 (Gleadthorpe) and 2 (Morley) and in 1978 at site 3 (Ropsley). The livestock manure treatments commenced in 1991 at sites 5 (Harper Adams) and 6 (Bridgets), 1992 at site 4 (Gleadthorpe) and 1994 at site 7 (Terrington).

At each site, there were 3 (organic materials) or 4 (crop residues) replicates of each treatment (depending on the original design of the experiment), arranged in a randomised block design. Plot sizes varied across the sites depending on the original design and aims of the experiment (sites 1 & 2: 16 x 4m; site 3: 15x 3m; site 4: minimum of 5 x 15m; site 5: 6 x 10m; site 6: 9 x 8m; site 7: minimum of 18 x 7m). All livestock manures at sites 5-7 were applied at a target rate of 250 kg N/ha and balanced with manufactured fertiliser N, using MANNER model predictions of manure crop available N availability (Chambers *et al.,* 1999), to ensure similarity of crop available N supply across the treatments (with the control treatment receiving the economic recommended rate of manufactured fertiliser N; Anon., 2000). At site 4 (Gleadthorpe), broiler litter was applied at 6 rates from 0 to 25 t/ha (fresh weight), and again balanced with manufactured fertiliser N to ensure similarity of crop available N supply across the treatments. Additionally, at the four organic material sites (sites 4-7), green compost (at 250 kg N/ha) and paper crumble additions (at 75 t/ha fresh weight) were introduced as new treatments in autumn 2004 (again balanced with manufactured fertiliser N), and cattle FYM and slurry (at 250 kg N/ha) was also added at Gleadthorpe (site 4) to match the design (solid *vs*. liquid manure) at the other three organic material sites.

Table 1. Experimental sites and established treatments

Site	% clay	SOC (g/kg)[a]	Treatment	No. years applied[b]	Net OC loading (t/ha)[c]
Crop residue experimental sites:					
1. Gleadthorpe	5	12	0-250 kg N/ha	21	23 (max)
2. Morley	13	10	0-250 kg N/ha	21	31 (max)
3. Ropsley	27	12	0-245 kg N/ha	28	38 (max)
Organic material experimental sites[d]:					
4. Gleadthorpe[e]	6	11	Broiler litter	14	0-98
5. Harper Adams	12	15	Cattle FYM & slurry	13	18 (slurry), 42 (FYM)
6. Bridgets	23	33	Cattle FYM & slurry	13	28 (slurry), 47 (FYM)
7. Terrington	28	14	Pig FYM & slurry	14	8 (slurry), 28 (FYM)

[a] SOC measured on the untreated control in autumn 1994 at sites 1 & 2 (Nicholson *et al.,* 1997), spring 1992 at site 3 (Bhogal *et al.,* 1997) and autumn 1998 at sites 4-7 (Bhogal *et al.,* 2009). See section 5.5 for details of changes in SOC during the course of the experiment.

[b] Number of years treatments were applied prior to soil sampling in spring 2005 (sites 1&2), 2006 (sites 3&4) or 2007 (sites 5-7). SOC was also sampled in autumn 2008 at all sites.
[c] OC loadings are net of the untreated control treatment up to the sampling dates specified in b (above).
[d] Compost and paper crumble applied (since 2004) at sites 4-7, supplying *c.*8 and 12 t/ha OC prior to soil sampling, respectively.
[e] Cattle FYM and slurry applied (since 2004) at site 4, supplying *c.*8 and 2 t/ha OC prior to soil sampling, respectively.

In order to evaluate the effects of ‘recent’ livestock manure OC additions (applied every year) compared with OC additions from ‘historic’ inputs (> 2 years old), plots at the organic material experimental sites were split and livestock manure additions *withheld* for 2 years from one half of each plot (‘historic’ treatment), with the other half receiving manure annually (‘recent’ treatment). All sites were managed as part of a conventional arable crop rotation growing combinable crops (cereals & oilseed rape) for the duration of the study (see Appendix 1 for details of the crops grown).

4.2 Nutrient and organic matter loadings

Each year (2004-2008 inclusive), the organic material additions were fully characterised (dry matter, total N, ammonium and nitrate N, uric acid N – poultry manure only, total P, K, Mg, S and total OC), according to standard analytical techniques (Anon., 1986), together with measurement of the total zinc-Zn, copper-Cu, nickel-Ni, cadmium-Cd, lead-Pb and chromium-Cr content of the poultry and pig manures applied at Gleadthorpe (site 4) and Terrington (site 7). Additionally, the substrate quality and potential decomposability of the organic material OC additions were characterised through the measurement of water extractable C, lignin and cellulose contents (Harper & Lynch, 1981), and the aerobic stability (evolved carbon dioxide) of the solid material additions (Llewelyn, 2005).

Total above ground biomass production (grain/seed + straw) was measured at each site at harvest and used to estimate the returns of C and N in roots, stubble and straw. These estimates assumed that half of the non-grain/seed biomass was returned in the stubble and chaff (Anon., 1997), that root dry matter production was equivalent to *c.*8% of shoot dry matter (Gregory *et al.,* 1978) and that all dry matter contained 40% OC (Powlson *et al.,* 1985). Crop residue inputs at the organic material experimental sites were assumed to be constant across all treatments, as crop available N supply was balanced and there were no consistent crop yield differences between the organic material and manufactured fertiliser N control treatments (see Section 4.1). Total OC loadings at these sites were therefore equivalent to total organic material OC inputs (Table 1).

4.3 Assessment of soil bio-physical and physico-chemical properties

Selected soil physical, chemical and biological properties were measured in spring 2005 (sites 1&2), 2006 (sites 3 & 4) and 2007 (sites 5-7); Table 2. All of the properties detailed in table 2 were measured at each site, unless otherwise stated in table 2. All soil analyses were performed on representative topsoil samples (0-15cm) taken from each replicated plot (consisting of *c.*25 cores bulked to give one composite sample per replicated plot), unless otherwise stated in Table 2.

Table 2. Measured soil bio-physical and physico-chemical properties and processes

Soil property[a]	Method
Chemical:	
Total OC	'Tinsley' (Anon., 1986)
Light fraction OC	Density separation (Gregorich *et al*., 1997)
Dissolved OC	water extractable C and K_2SO_4 extractable C.
Total N, total S[b]*, pH, extractable P, K & Mg*	Total N by 'Kjeldhal', Total S by combustion; pH in water; 'Olsen' extractable P, Ammonium nitrate extractable K and Mg (Anon., 1986)
Cation exchange capacity	Extraction with ammonium acetate/potassium chloride (Anon., 1986)
Total metals (Zn, Cu, Ni, Cd, Pb, Cr)[c]	Aqua-regia (1.6:1 Hydrochloric:nitric acids) digestion (Anon., 1986)
Biological:	
Biomass C & N	Chloroform-incubation (Jenkinson & Powlson, 1976). Correction factor = 2.22 (Wu *et al.,* 1990)
Respiration	Alkali (KOH) absorption (Anderson, 1982)
Active fungal biomass	Ergosterol concentrations (Eash *et al.,* 1996)
Potentially mineralisable N (PMN)	Anaerobic incubation (Keeney, 1982)
Potentially mineralisable S (PMS)[b]	Aerobic incubation (14 days) and extraction with KH_2PO_4.
Soil fauna[b]	Earthworms: Formalin drench (Raw, 1959) Springtails (Collembola): Tullgren funnel (Tullgren, 1918) Free-living nematodes: (Flegg, 1967)
Physical:	
Available water capacity	Volumetric moisture content between 0.05 and 15 bar (Anon., 1982)
Bulk density	5 intact soil cores per plot (Anon., 1982)
Porosity	Porosity = 1-(bulk density/particle density)*100; where particle density=2.65 (Anon., 1982)
Shear strength	10 'Pilcon' shear vane to 7.5 cm per plot (Anon., 1982)
Penetration resistance	10 Penetrometer readings to 15cm per plot (Anon., 1982)
Aggregate stability	*Dispersion ratio (in sodium hexametaphosphate) on 5-30mm aggregates (Anon., 1982)* & Le Bissonnais crusting assessment (Le Bissonnais, 1996)
Structural regeneration	Cracking pattern analysis: measurements of crack porosity, heterogeneity & connectivity (Preston *et al.,* 1997, 1999)
Infiltration rates	Field: double ring infiltrometer (selected treatments) Lab: Water repellency of sieved air dried soil using the sorptivity method described in Hallett &Young (1999).
Plough resistance[d]	Draught forces measured using a tractor mounted vertical tine fitted with a strain-gauge (Sharifi *et al.,* 2007; see Appendix 2).
Resistance to wind erosion[d]	Wind tunnels with a particle trap (see Appendix 2)
Resistance to water erosion[d]	Mobile rainfall simulator (Grierson & Oades 1977), with measurement of the time to runoff, fragmentation of the surface layer, hydraulic conductivity and critical shear stress (Watts *et al.,* 2003). See Appendix 2

[a] *The measurements in italics are repeats of those carried out in SP0501 and SP0504.*

[b] Organic material experimental sites only

[c] At Gleadthorpe (site 4) and Terrington (site 7) only, where pig and poultry manures were applied (as these manure types are susceptible to high metal concentrations due to dietary supplementation; Nicholson *et al.,* 2003).

[d] Plough resistance at sites 3 (Ropsley) & 4 (Gleadthorpe); Resistance to wind erosion at site 4 (Gleadthorpe); Resistance to water erosion at sites 1 (Gleadthorpe crop residues) & 4 (Gleadthorpe organic materials). These methods are very labour intensive so were only conducted at the potentially more responsive crop residue and organic material sites i.e. the sandy erosion-sensitive soil at Gleadthorpe (sites 1 & 4) and Ropsley (site 3) which had received differential crop residue inputs for the longest period of time.

4.4 Data analysis and modelling

Relationships between OC loadings and changes in soil properties were explored using parallel line analysis techniques (using Linear Regression with Groups within Genstat Release 11.1, VSN International Ltd 2008). This is a very powerful tool, enabling relationships to be established across sites (and treatments) that have predictive capability. Total OC loading (i.e. OC applied in the form of livestock manures, compost, paper crumble and additional crop residues net of the control treatment) was used as the predictor (x-axis) in order to derive changes in soil properties per unit of applied OC. SOC at the time of sampling, did not prove to be a useful predictor of change due to different background SOC contents at each of the sites, which were very large relative to the input of OC in the form of organic materials and crop residues. Although the experimental design differed across the sites, there was insufficient data to derive relationships separately for each individual site. Therefore, results from all the sites were pooled and expressed as a percentage difference from the untreated control treatment, in order to normalize the data across the different sites and treatments, and to enable relationships to be established across the full range of OC inputs. This inevitably resulted in site 4 (with the highest OC loadings due to differential rates of broiler litter application, Table 1) having a strong influence on the statistical analysis as a result of the higher long-term inputs. However, the lignin content of the solid manure applications was very similar across the manure types (at *c*.30% of TOC, Figure 1 & Appendix 3), indicating that the contrasting livestock manure OC sources were likely to have a similar impact on soil properties. In order to explore the influence of site 4 on the results, the analysis was performed first for site 4 only and then with the inclusion of the other three organic material sites (sites 5-7, where there was an insufficient range of C loadings to perform the analysis separately). There was no significant change ($P>0.05$) in the derived relationships by inclusion of the results from sites 5-7, with these sites showing similar trends with the same direction of change, albeit at the smaller range of OC inputs. Separate relationships were derived (where appropriate) for ‘organic materials’ (i.e. livestock manures, compost & paper crumble) and crop residues, as well as for ‘recent’ and ‘historic’ livestock manure additions. The compost and paper crumble additions were grouped with the livestock manures (termed ‘organic materials’) as these treatments had only been in place for 2-3 seasons prior to sampling.

The rate of change in SOC levels and effect of different management scenarios on SOC was evaluated through carbon turnover modelling, using the ROTH-C carbon model (Coleman & Jenkinson, 1996).

5. Results and discussion

5.1 Crop yields, residue returns and organic carbon loadings

The results showed that grain/seed yields increased with fertiliser N application rate at all of the crop residue experimental sites (sites 1-3), in all but one of the 15 site/seasons (3 sites x 5 seasons) studied ($P<0.05$ except at site 1 in 2006; Appendix 1). As a result, the returns of C in straw, stubble and roots (calculated as described in Section 3.2) also increased with fertiliser N rate ($P<0.05$; Appendix 1). Total C inputs (straw, stubble & roots, net of the untreated control from experiment inception up to and including harvest 2007) ranged from 13 to 42 t/ha at these sites (sites 1-3; Table 3).

Table 3. Total OC inputs and topsoil OC retention.

Site	No. of years of additions	C loading^{a} (t/ha)	SOC range (g/kg)^{b}	⇧ SOC^{b} (t/ha)	% C retention^{c}
Crop residue experimental sites:					
1. Gleadthorpe	24	16-27	11-14	0-13	0-50
2. Morley	24	17-35	8-9	1-3	2-8
3. Ropsley	30	13-42	11-14	1-11	5-26
			Average C retention:		***19.5*** *± 4.2*
Organic material experimental sites:					
4. Gleadthorpe	16	23-113	9-17	7-29	15-36
5. Harper Adams	14	19-47	12-15	4-9	18
6. Bridgets	14	30-50	27-33	4-14	12-28
7. Terrington	15	8-30	14-21	5-24	65-79
			Average C retention:		***30.6*** *± 6.6*

[a] OC loading up to autumn 2007 (including 2007/08 manure additions), expressed as a difference from the untreated control treatment

[b] Range in SOC contents measured at the sites in August 2008 (untreated control and top level)

[c] Increase in topsoil SOC to 25cm (35cm at Gleadthorpe), relative to the untreated control, measured August 2008 (bulk density measured in spring 2005 (sites 1&2), 2006 (sites 3 & 4) and 2007 (sites 5-7)).

[d] C retention = (⇧ SOC/C loading)*100; calculated on an individual treatment basis at each site, then averaged across all sites and treatments.

At the organic material experimental sites, supplementary manufactured fertiliser N was applied at recommended rates according to MANNER predictions of manure crop N availability (Chambers *et al.,* 1999) to ensure similarity of crop available N supply across the treatments (with the control treatment receiving the full economic rate of manufactured fertiliser N; Anon, 2000). This enabled an assessment of the potential additional benefit of manure additions to crop productivity, over and above its value as a source of N, as demonstrated in the classical experiments at Rothamsted (Johnston, 1986). Generally, there were no consistent crop yield differences between the organic material and manufactured fertiliser N control treatments at any of the sites that would suggest a specific benefit of manure additions *per se* (Appendix 1). However, yields increased ($P<0.05$) with broiler litter application rate at Gleadthorpe in 2 of the 5 study years, and with FYM applications at Bridgets and Terrington in 1 of the 5 study years, which were most probably due to the incorrect balancing of crop available N supply, which is widely recognised as being difficult to achieve (Anon, 2000; Chambers *et al.,* 1999). At Harper Adams, yields were generally consistent across all treatments, except on the paper crumble treatment in 2005 and 2006, where there was a significant reduction in grain yield (*P*<0.01), which was most probably due to N immobilisation by the paper crumble, and the absence of any additional compensatory manufactured fertiliser N applications. There were also some problems with harvesting the oilseed rape crops in 2004 and 2007 at this site, due to heavy rainfall and associated crop lodging at harvest.

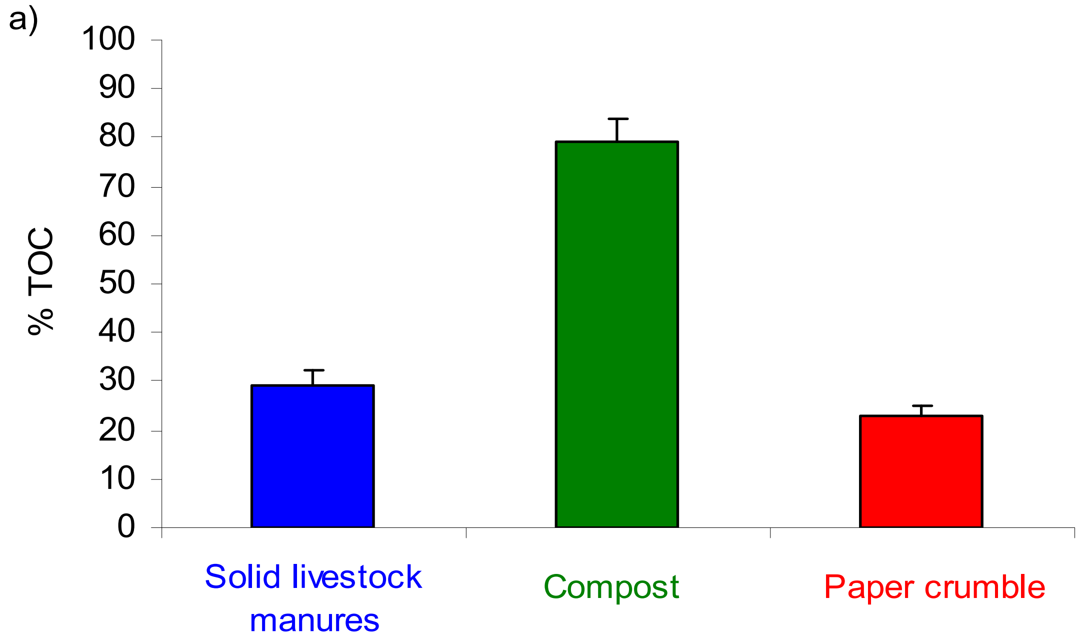
The differences in yield and therefore crop residue OC inputs noted above were small relative to the accumulated manure OC inputs. For example, the 2 t/ha difference in grain yield measured at Terrington in 2006 (the maximum yield difference measured at any of sites 4-7 throughout the whole experimental period; Appendix 1) equated to *c.*1.2 t/ha additional OC input in straw, stubble and roots (using the assumptions outlined in Section 4.2) which is *c*.4% of the total accumulated OC inputs from FYM additions at this site (i.e. 30 t OC/ha; Table 3). Given the difficulty in measuring small changes in SOC due to the large background of OC already present in soils (Powlson *et al.,* 1987), these relatively small and inconsistent differences in crop residue OC inputs at the manure experimental sites are not likely to have significantly affected the overall results and conclusions. Hence, crop residue C inputs at these sites (4-7) were assumed to be constant across all treatments, with differences in OC loadings at these sites equivalent to differences in total manure OC inputs. A summary of the nutrient composition of the organic materials applied at each site is given in Appendix 3. Total manure OC loadings (from experiment inception up to and including the autumn 2007 applications) ranged from 8 to 113 t/ha (excluding the compost & paper crumble treatments; Table 3).

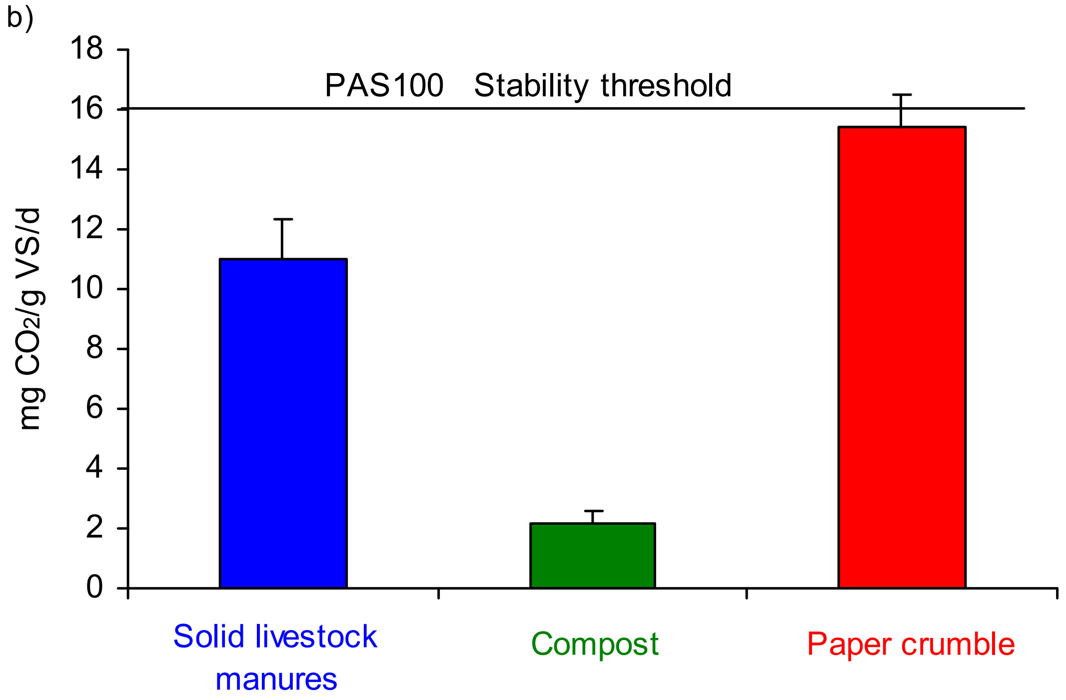
The increases in topsoil SOC (relative to the untreated control at each site) measured in August 2008 following 14-16 years of annual livestock manure additions and 24-30 years of differential crop residue returns represented *c.*31% of total livestock manure OC inputs and *c.*20% of total crop residue inputs (Table 3). This indicates that 70-80% of total OC inputs had been oxidised and lost from the topsoil (largely as carbon dioxide to the atmosphere), with the retention of OC in the topsoil greater for more ‘resistant’ C sources i.e. livestock manures compared with crop residues. In grassland soils, Jones *et al*. (2006) measured between 27-39% retention of the OC applied in sewage sludge and livestock manures over a 6 year period. Similarly, Gibbs *et al.* (2006) measured 36-55% retention of the OC applied in sewage sludge to arable and grassland soils over a 4 year period. The slightly lower OC retention measured at the SOIL-*QC* experimental sites is probably due to the longer time frame over which the experiments have been running (14-30 years). However, the findings are consistent with the conclusions of Jenkinson (1988) that the proportion of total OC remaining in the soil, once the initial rapid phase of decomposition has occurred, is similar for a wide range of residues, with approximately one-third of the residue OC remaining one year after application.

5.2 Organic material characterisation

An important aspect of this project was characterisation of the organic material additions applied at sites 4-7 according to their carbon composition (i.e. total OC, lignin, cellulose & dissolved OC; Appendix 3), with the lignin fraction considered to be ‘stable’, and the cellulose and dissolved OC pools more ‘readily decomposable’. The most stable material was green compost, with *c*.80% of total OC (TOC) in the ‘stable’ (lignin) pool (Figure 1a). The solid livestock manures (cattle, pig and poultry) had similar OC compositions with *c.*30% of total OC in the 'stable' pool, and paper crumble the lowest (*c.*20% in the 'stable' pool). The PAS100 aerobic stability test (Llewelyn, 2005) gave a similar ranking of organic materials (Figure 1b), with a lower CO_2 evolution indicating greater stability. All materials were below the PAS100 stability threshold of 16 mg CO2/g VS/d (BSI PAS 100), which is the maximum CO_2 evolution rate considered to be acceptable for a quality compost (i.e. above this threshold a compost is considered to be unstable). These data have proved particularly valuable to the ROTH-C modelling exercise detailed in Section 4.5.

Figure 1. Stability of the organic material additions at sites 4-7: a) Lignin content (% of total OC content), b) PAS100 Aerobic stability. Data are a mean of analyses undertaken from 2005-2007 at sites 4-7 (Appendix 3).





5.3 Metal content of pig and poultry manures

Livestock manures are an important source of metal additions to agricultural land and were estimated to be responsible for *c*.30% of total zinc and copper inputs in the UK in 2008, with pig and poultry manures having the highest concentrations reflecting dietary supplementation (Defra project SP0569). The metal concentrations in the pig and poultry manures applied at Terrington and Gleadthorpe, respectively, are given in Table 4; and were within the reported range of values for these manure types (Defra project SP0569).

Table 4. Metal concentrations (mg/kg dry matter) in the pig and poultry manures applied at Terrington and Gleadthorpe, respectively. Data are a mean of five annual applications, with the range of reported values from Defra project SP0569 given in parenthesis.

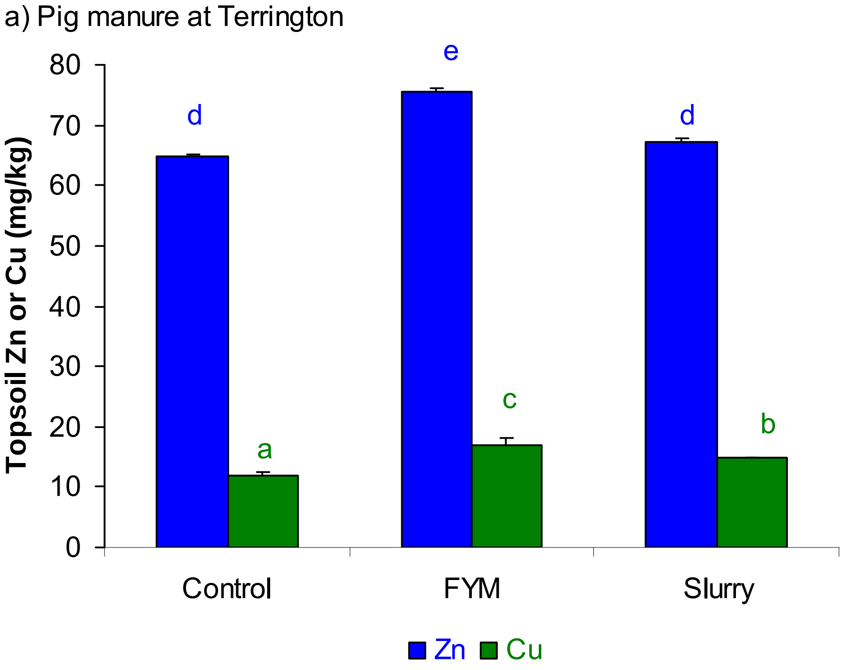
Manure	Zn	Cu	Ni	Cd	Pb	Cr
Pig FYM[a]	822 (146-1830)	461 (26-707)	5.2 (1-109)	0.4 (0.1-1.3)	4.8 (2.5-171)	5.2 (2.0-190)
Pig slurry[a]	954 (66-5174)	373 (20-1333)	27 (1-16)	2.5 (0.1-7.5)	46 (2.5-31)	9.1 (0.5-16)
Broiler litter[b]	356 (152-526)	88 (41-127)	4.8 (1-7.2)	0.3 (0.1-0.7)	2.8 (2.5-29)	5.0 (1.5-10)

[a]Terrington 2004-2008

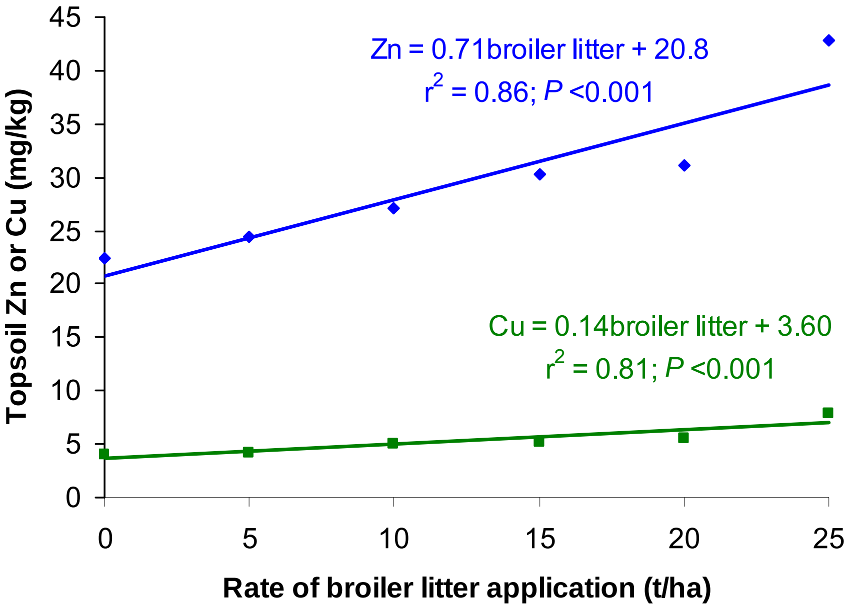
[b]Gleadthorpe 2004-2008

Repeated addition of these manures resulted in small zinc (range: 11-20 mg/kg) and copper (range: 4-5 mg/kg) concentration increases in the topsoil (*P*<0.05; Figures 2a&b), which in the long-term following repeated additions may have impacts on soil quality and fertility (Anon., 2009). However, concentrations were well below maximum permissible concentrations in soils after sewage sludge application (200 mg/kg Zn, 135 mg/kg/Cu at pH 6.0-7.0; Anon., 2009).

Figure 2. Effect of a) pig (Terrington) and b) poultry (Gleadthorpe) manure additions on topsoil zinc and copper concentrations. Bars with different letters are significantly different from each other at *P*<0.05.



b) Poultry manure at Gleadthorpe



5.4 Response in soil bio-physical and physico-chemical properties to organic C loadings

5.4.1 Effect of form of organic addition

Organic C inputs in the form of livestock manures (FYM, slurry, broiler litter) changed a large number of soil properties (Table 5). In contrast, there were relatively few changes resulting from crop residue OC inputs, reflecting the lower input and retention of OC at the crop residue sites (Tables 2 & 3). Soil chemical and biological properties were the most responsive to OC additions, with a large number of soil physical properties un-affected. The compost and paper crumble additions had only been applied to the organic material experimental sites for 2-3 years prior to sampling and therefore had relatively low OC loading rates, however, for most soil properties they showed similar trends to the livestock manure applications (see Figures 3-5, 8 & 10). Hence, all these inputs were grouped in subsequent analyses, with the term ‘organic materials’ used to cover all livestock manure, paper crumble and green compost inputs.

Soil chemical properties

Topsoil organic C (SOC) ranged from 7-30 g/kg (13-43 t/ha) on the untreated control treatments (Appendix 4). SOC levels increased by *c.*7% with every 10 t/ha ‘organic material’ OC applied (Fig. 3a). This equates to an absolute increase in topsoil C stocks of *c.*0.47 t OC/ha/yr as an average over the experimental period. Estimates of the C storage potential of FYM applications have been shown to vary approximately 7-fold from 0.2 to 1.5 t/ha/yr, with a ‘best estimate’ of 0.4 t/ha/yr (Smith *et al.,* 2005), which is almost identical to the value of 0.47 t/ha/yr in this project. There was no relationship (*P*>0.05) with crop residue C inputs, even though SOC tended to be elevated above the unfertilised control treatments. The light fraction organic carbon (LFOC, Fig. 3b) and dissolved (water soluble) OC pools (Fig. 3c) were more responsive than the total SOC pool (*c.*23% increase in LFOC and 18% increase in DOC with every 10 t/ha OC input), with again no relationship measured in relation to crop residue OC inputs. The LFOC represented *c.*6% of the total SOC pool on the untreated control. The soil chemical properties at all sites and treatments is presented in Appendix 4, Tables 1&2.

Table 5. Response in soil properties to organic C loadings.

Property	Response to organic material OC loading (r^2)[a]	Response to crop residue OC loading (r^2)[a]	Same response to 'historic' and 'recent' livestock manure OC additions (r^2)[b]
Chemical:			
Organic C (total)	⇧ (0.68)	X	✓ (0.79)
Light fraction OC	⇧ (0.72)	X	~ (0.81): divergent
Dissolved OC	⇧ (0.46)	X	✓ (0.28)
Total N	⇧ (0.67)	⇧ (0.19)	✓ (0.78)
Extractable P	⇧ (0.66)	⇩ (0.33)	✓ (0.45)
Extractable K	⇧ (0.51)	⇩ (0.63)	~(0.57): parallel
Extractable Mg	X	X	No fit
pH	X	X	No fit
CEC	⇧ (0.51)	X	✓ (0.76)
Biological:			
Biomass N	⇧ (0.52)	X	✓ (0.67)
Biomass C	X	X	No fit
Fungi (ergosterol)	⇧ (0.52)	⇧ (0.33)[e]	~ (0.47): single
Respiration	X	X	No fit
Potentially mineralisable N	⇧ (0.57)	X	✓ (0.72)
Physical:			
Available water capacity	⇧ (0.39)	X	✓ (0.49)
Easily available water capacity	⇧ (0.52)	X	✓ (0.64)
Porosity	⇧ (0.59)	X	✓ (0.59)
Bulk density	⇩ (0.54)	X	✓ (0.57)
Shear strength	X	X	No fit
Penetration resistance	⇩ (0.23)	⇩ (0.36)	✓ (0.38)
Aggregate stability[c]:			
Dispersion ratio	X	X	No fit
Le Bissonais	X	⇧ (0.44)[f,]	No fit
Cracking patterns	X	X	No fit
Infiltration rates[d]	X	ND	ND
Plough resistance[d]	X	X	ND
Resistance to wind erosion[d]	X	ND	ND
Resistance to water erosion[d]	X	X	ND

[a] ⇧ indicates a positive response (increase) to OC loading ($P<0.05$); ⇩ indicates a negative response (decrease) to OC loading ($P<0.05$); X indicates no response to OC loading ($P>0.05$); Organic materials *include* paper crumble and compost treatments, although these had relatively low C loadings after only 2-3 years of application; r^2 of the regression analysis given in parenthesis; ND: not determined.

[b] ✓ indicates no difference in the response to 'historic' and 'recent' *livestock manure* OC additions (sites 4-7 only); ~ indicates different response to 'historic' and 'recent' additions: divergent = recent treatment showed greater rate of response compared to the historic treatment, parallel = recent treatment showed a proportional upward shift in response, single: only the recent treatment showed a response; r^2 of the parallel line fit given in parenthesis;

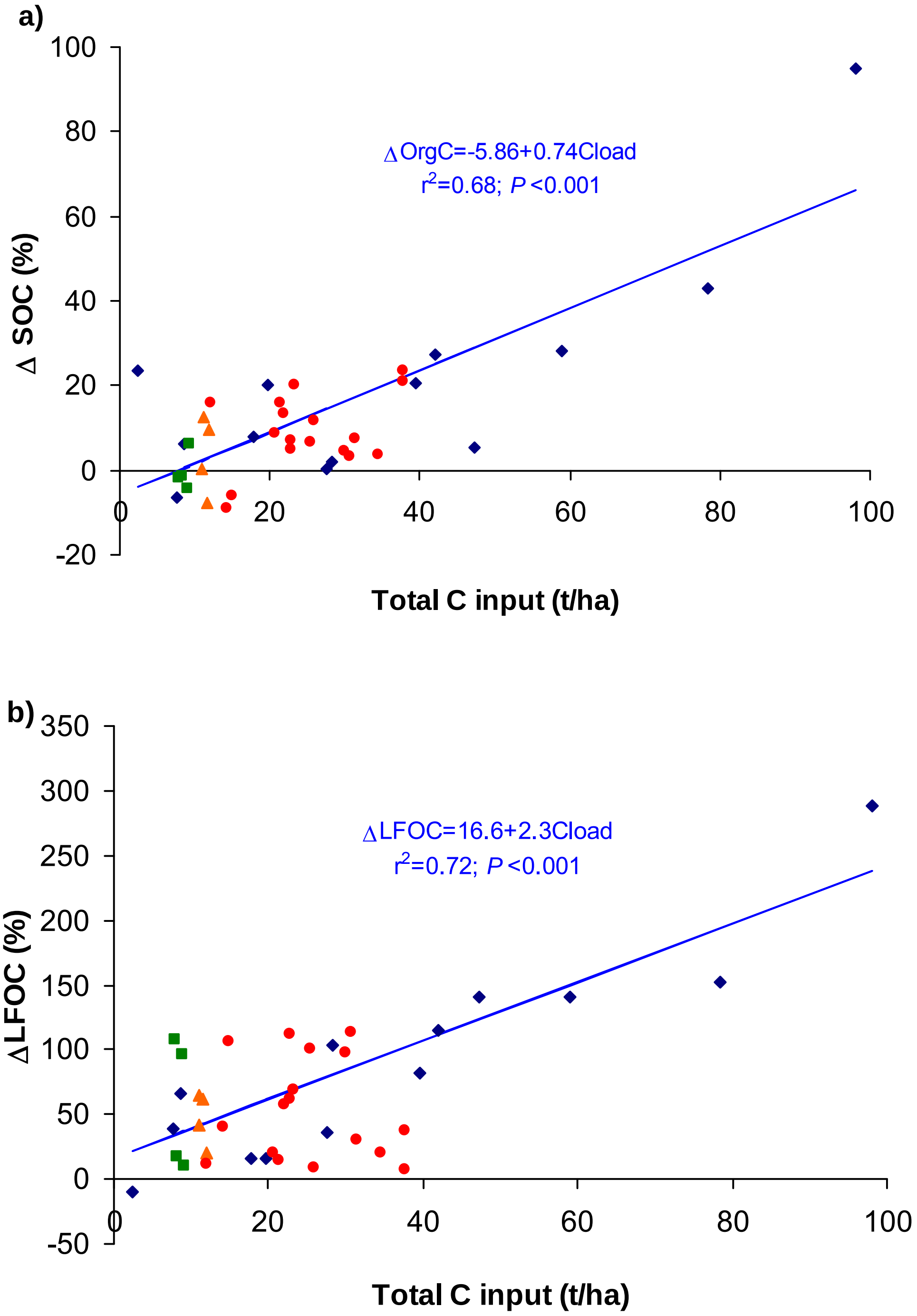
[c] Aggregate stability measured by both the Dispersion Ratio and Le Bissonais techniques.

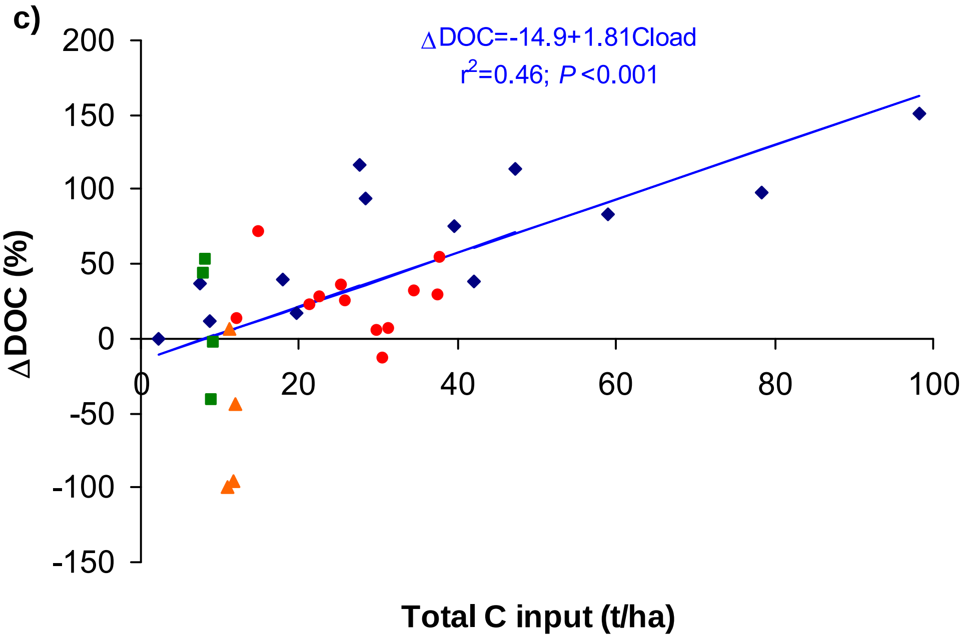
[d] Infiltration rates measured at sites 4-7; Plough resistance at sites 3 & 4; Resistance to wind erosion at site 4; Resistance to water erosion at sites 1 & 4.

[e] Data from Morley excluded from the relationship – the untreated control treatment at this site had a spuriously low fungal biomass at <0.3 mg/kg on all 4 replicate plots (*c.*1.0 mg/kg is typical for an arable soil; I. Young, SIMBIOS, pers.comm). As a result the response to increased crop residue C inputs (expressed as a percentage difference from the control) was much greater than that measured at all other sites.

[f] Increase in mean weight diameter of aggregates after fast wetting indicates an increase in stability (resistance to slaking) with increasing crop residue C inputs.

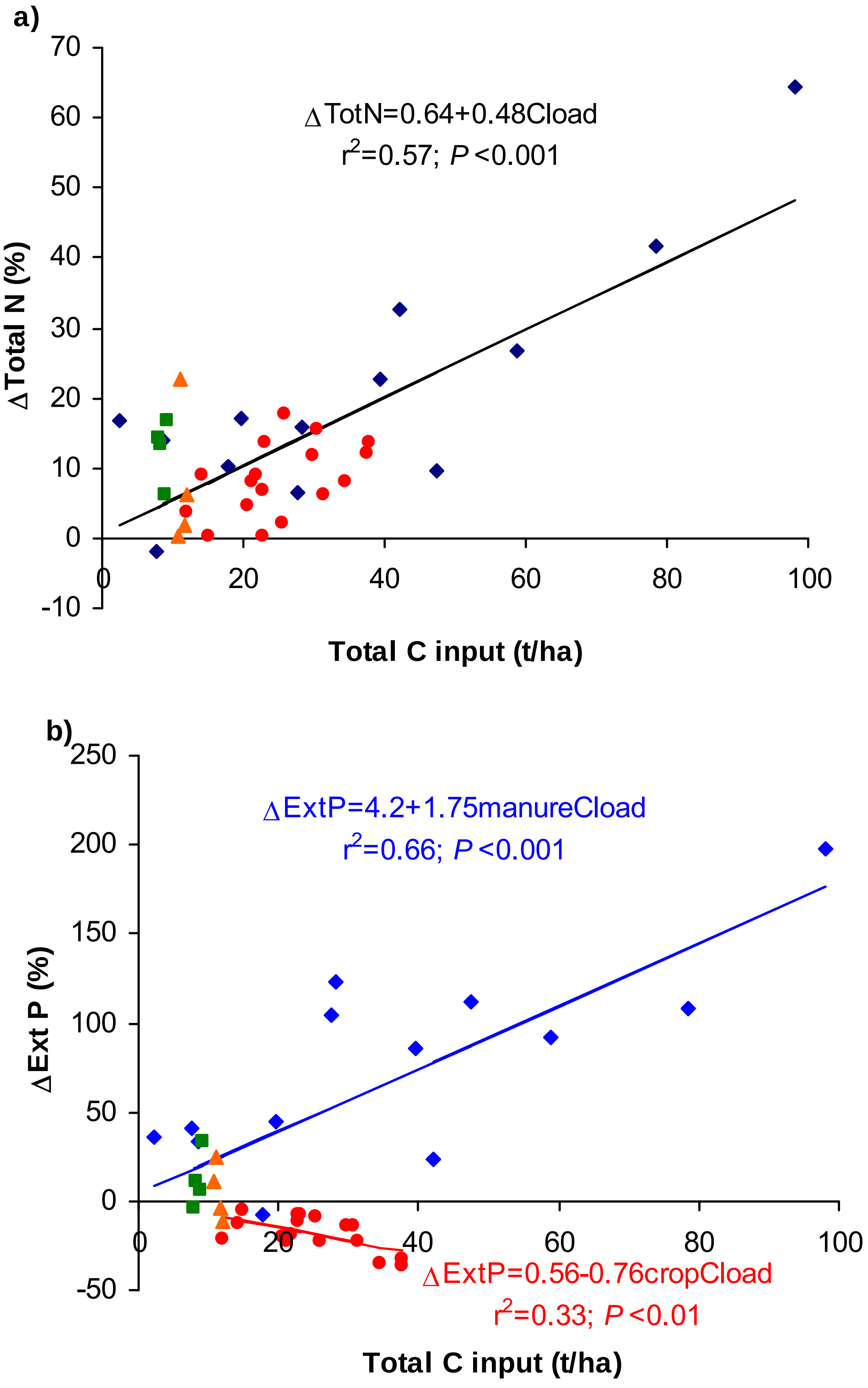
Figure 3. Change in topsoil a) total soil organic carbon (SOC), b) light fraction organic carbon (LFOC) and c) dissolved organic carbon (DOC), with total carbon inputs in the form of ‘organic materials’ (livestock manures (◆), compost (■) and paper crumble (▲)), and crop residues (●). Results are expressed as a percentage difference from the untreated control treatments. Blue line indicates a relationship between the ‘organic material’ OC inputs and soil properties only.



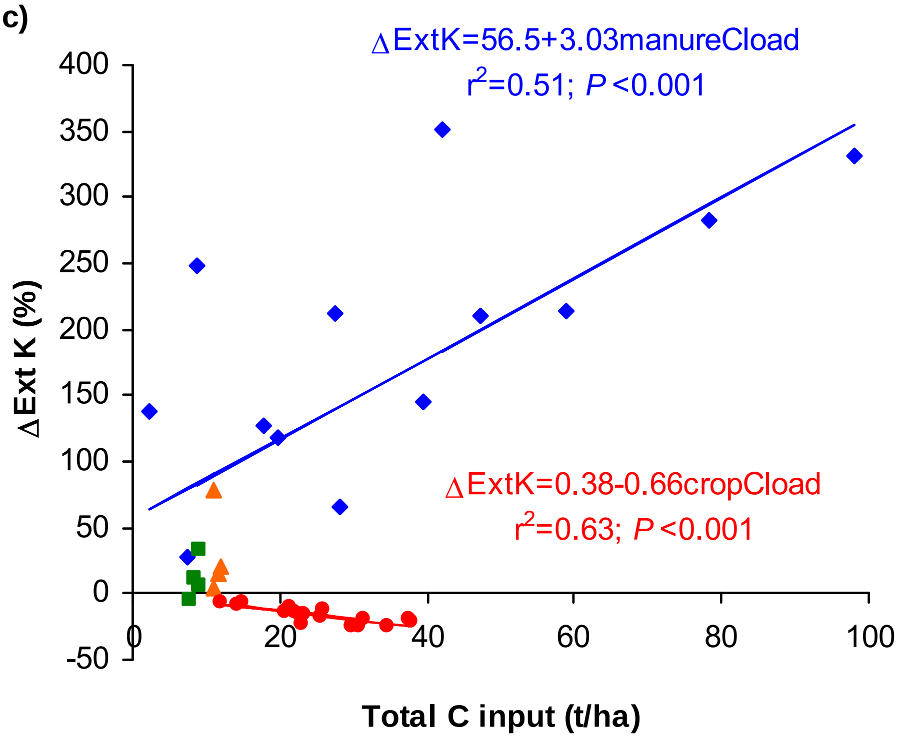


Topsoil total N increased by *c.*5% with every 10 t/ha ‘organic material’ and crop residue OC inputs (based on regression analysis); notably, there was a response to crop residue OC additions which was similar (P>0.05) to that measured from the ‘organic material’ OC additions (Fig. 4a). In contrast, topsoil nutrient status (extractable P and extractable K) decreased with increasing crop residue C inputs at the crop residue experimental sites 1-3 (Figs. 4b&c) which was due to greater crop yields and associated nutrient offtakes at the higher manufactured fertiliser N rates. At these sites (numbers 1-3), winter wheat grain yields on the unfertilised controls ranged from 1.5-4.2 t/ha (mean: 2.5 t/ha) during the experimental period (2004-2008), compared with 4.8-10.9 t/ha at the highest manufactured N application rates (mean: 7.7 t/ha); Appendix 1. As livestock manures and compost are a valuable source of phosphate and potash (Anon, 2000 & Appendix 3) topsoil extractable P and K levels increased with ‘organic material’ OC inputs (Figs. 4b&c). Moreover, farmers can reduce the use of manufactured NPK fertilisers and make considerable financial savings through the application of livestock manures and compost, with a typical application of cattle FYM (at 250 kgN/ha) estimated to save *c.* £158/ha and green compost (at 250 kgN/ha) *c.* £90/ha in fertiliser inputs (Bhogal *et al.,* 2007). Topsoil pH ranged from 6.0-8.5 on the untreated control treatments and was not affected by organic material or crop residue OC inputs. There was also no response (P>0.05) in topsoil extractable Mg levels. Notably, the soil cation exchange capacity (CEC) increased by *c.*4% with every 10 t/ha ‘organic material’ OC applied (Fig. 4d), however, there was no relationship (P>0.05) with crop residue OC inputs. Humic substances (i.e. SOM) are important to CEC, often contributing to over half of the total soil‘s capacity to exchange cations (Jenkinson, 1988).

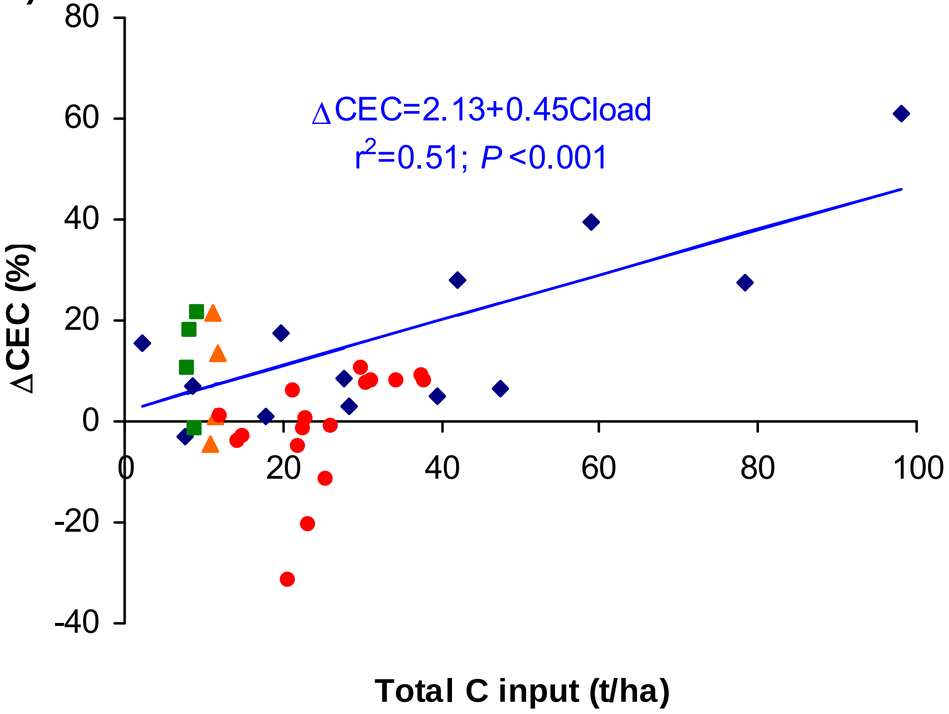
Figure 4. Change in topsoil a) total nitrogen, b) extractable phosphorus-P, c) extractable potassium-K and d) cation exchange capacity-CEC, with total carbon inputs in the form of 'organic materials' (livestock manures (◆), compost (■) and paper crumble (▲)), and crop residues (●). Results are expressed as a percentage difference from the untreated control treatments. Black line indicates a relationship between both 'organic material' and crop residue OC inputs; blue line indicates a relationship between the 'organic material' OC inputs only, and red line indicates a relationship between the crop residue OC inputs only.



c)


ΔExtK=56.5+3.03manureCload
r^2=0.51; *P* <0.001
ΔExtK=0.38-0.66cropCload
r^2=0.63; *P* <0.001
ΔExt K (%)
400
350
300
250
200
150
100
50
0
-50
0
20
40
60
80
100
Total C input (t/ha)

d)


ΔCEC=2.13+0.45Cload
r^2=0.51; *P* <0.001
ΔCEC (%)
80
60
40
20
0
-20
-40
0
20
40
60
80
100
Total C input (t/ha)

Soil biological properties

Historically, measurements of soil physical and chemical properties have predominantly been used to define soil quality, with the biological component largely ignored - even though this component can be highly sensitive to change (Kennedy & Smith, 1995). Measurements of soil microbial biomass size (i.e. carbon and nitrogen contents) and activity (i.e. respiration) provide an indication of a soil's ability to store and recycle nutrients and energy. In general, higher soil microbial biomass and respiration rates are linked with 'better' soil quality (Dick, 1992). Topsoil biological properties at all the sites and treatments are given in Appendix 4, Tables 3 & 4. Microbial biomass C ranged from 52 to 743 mg/kg on the untreated control treatments, with no consistent response to either organic material or crop residue OC inputs at any of the sites or treatments. In contrast, microbial biomass N ranged from 20 to 180 mg/kg on the untreated control treatments and increased by *c*.8% with every 10 t/ha organic material OC applied (Fig. 5a). There was no relationship with crop residue OC inputs (and increasing manufactured N applications), although the application of manufactured fertiliser N generally increased biomass N above the unfertilised control treatments. The discrepancy in response between the microbial biomass C and N pools is probably due to the high variability that can be associated with biomass C estimates (Bhogal *et al.,* 2009). Hence, the biomass C results should be treated with caution and biomass N used as a more reliable estimate of the size of the microbial biomass in this study.

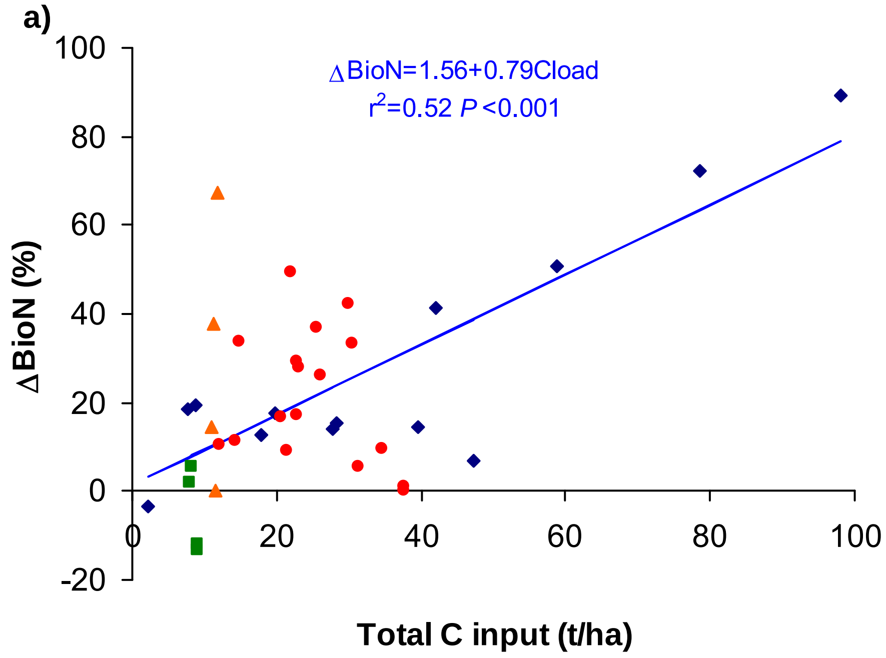
The fungal biomass is considered to play a key role in soil aggregation, due to the production of polysaccharide 'glues' and via physical enmeshment of soil particles by fungal hyphae (Tisdall & Oades, 1982; Eash *et al.,* 1994). Ergosterol is a carbohydrate located in the cellular membrane of 'living' fungi and is considered to be a bio-indicator of the amount of active fungal biomass within soils (Eash *et al.,* 1996). Topsoil ergosterol (fungal biomass) concentrations increased with both 'organic material' and crop residue OC inputs, with no difference ($P>0.05$) observed between the contrasting types of OC addition, except at site 2 (Morley), where the increase in fungal biomass was improbably large (Fig. 5b). Here, the fungal biomass was spuriously low on the untreated control (at <0.3mg/kg on all four replicates of this treatment; Appendix 4) and therefore resulted in an improbably large response to crop residue C inputs (as results were expressed as a difference from the untreated control). Arable soils typically contain *c*.1.0mg/kg fungal biomass (I. Young, SIMBIOS, pers. comm.). It is unclear why the fungal biomass on the control treatment at Morley (site 2) was so low, with concentrations ranging from 0.7-4.2 mg/kg on the control treatments at the other 6 sites (Appendix 4). Notably, using fungal biomass data from the lowest N application rate treatment (0.5 mg/kg biomass), instead of the untreated control, resulted in a similar response to increasing OC inputs as measured at the other sites (i.e. ∆Fungi:10-50%). In the absence of site 2 data, a 9% increase in fungal biomass was measured with every 10 t/ha OC applied.

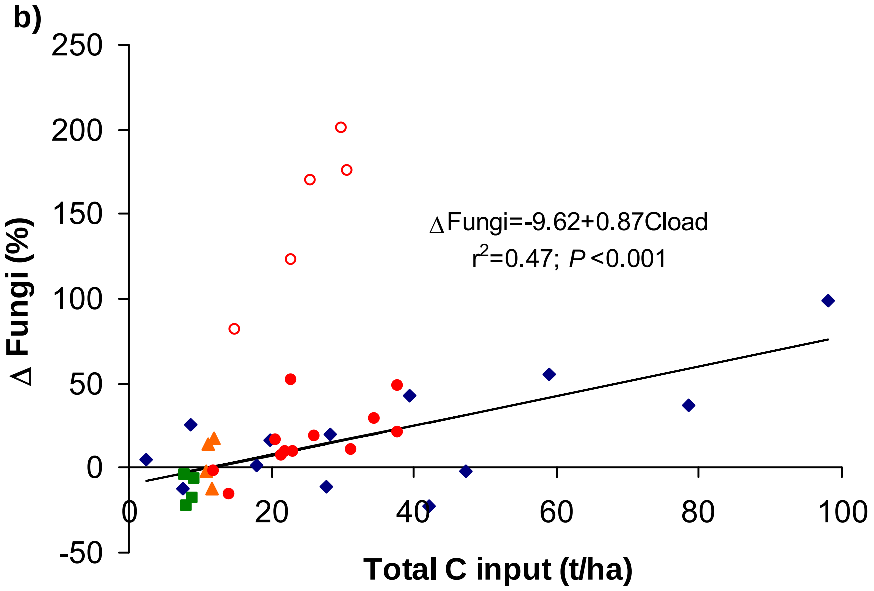
There was no relationship between OC loadings and soil respiration rates ($P>0.05$), although respiration rates tended to be higher with 'organic material' (range: 0.5 to 2.9 mg CO_2-C/kg/hour) and crop residue (range: 0.5 to 1.4 mg CO_2-C/kg/hour) OC inputs (compared with untreated control respiration rates in the range 0.3 to 1.9 mg CO_2-C/kg/hour).

The potentially mineralisable N pool (PMN) showed the greatest response to 'organic material' OC inputs, with an increase of *c*.22% for every 10 t/ha OC applied (Fig. 5c).

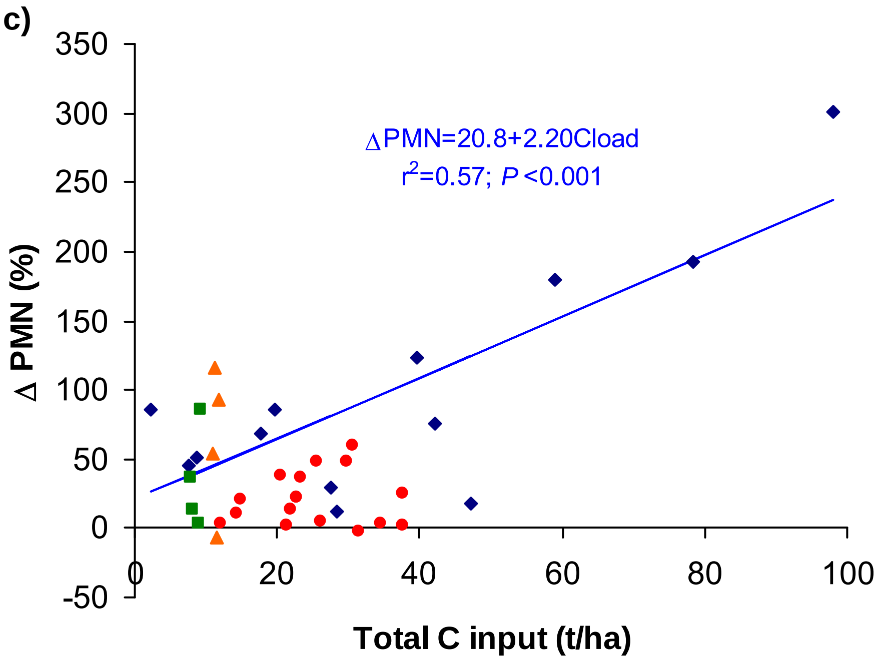
However, there was no response (*P*>0.05) to crop residue OC inputs. This is not surprising as livestock manures have a lower C:N ratio (typically 4-15:1, Chadwick *et al*., 2000) than cereal crop residues (typically 65:1 for wheat straw) and therefore supply more N per unit of OC input, which is considerably more 'mineralisable' than that from crop residues.

Figure 5. Change in topsoil a) biomass nitrogen, b) fungal biomass (ergosterol) and c) potentially mineralisable N (PMN), with total carbon inputs in the form of 'organic materials' (livestock manures (◆), compost (■) and paper crumble (▲)), and crop residues (●). Results are expressed as a percentage difference from the untreated control treatments. Black line indicates a relationship between both 'organic material' and crop residue OC inputs; blue line indicates a relationship between the 'organic material' OC inputs only.





Regression excludes data from Morley (○)



Soil fauna

Fauna such as nematodes, collembola (springtails) and earthworms play a vital role in soil organic matter turnover, nutrient cycling and the development of soil structure, and are widely regarded as a soil component that is vulnerable to management changes (Blair & Bohlen, 1996; Stork & Eggleton, 1992). For example, increases in both earthworm and nematode populations have been measured following cattle and pig slurry additions to soils, with nematodes appearing to stimulate N mineralisation (Opperman *et al.,* 1993; Griffiths *et al.,* 1998; Unwin & Lewis, 1996). Measurements of three key soil faunal groups (microfauna - free living nematodes; mesofauna - mites, springtails & enchytraeid worms; macrofauna - earthworms) were undertaken at the organic material experimental sites, where accumulated OC inputs were the greatest (sites 4-6 only; full data set in Appendix 5):

- Free living nematodes were classified according to their feeding strategies (i.e. bacterial, omnivores, predators and plant feeders). As plant feeders are of most agronomic importance these were further classified according to the damage they can inflict on plants. However, none of the latter group was present in sufficient concentrations to cause concern (i.e. to justify application of a nematicide). Notably, increasing rates of broiler litter application at site 4 (Gleadthorpe) resulted in a decrease ($P<0.05$) in the population of ‘stubby root’ nematodes to very low levels at the 25 t/ha application rate (Figure 6). This group of nematodes can cause docking disorder (stunted plants) and fanged roots in sugar beet and carrots, as well as being a virus vector (e.g. causing spraing or ‘corky ring spot’ in potatoes).

- There was no effect (*P*>0.05) of organic material additions on soil mesofauna (i.e. mites, springtails and enchytraeid worms), although populations tended to be greater on the sandy soil at Gleadthorpe (site 4).

- The application of cattle FYM at both Gleadthorpe (site 4) and Harper Adams (site 5) tended to increase earthworm populations (Figure 7a); this was most probably due to the presence of earthworms within the FYM itself (i.e. 'imported' onto the sites). Also, increasing rates of broiler litter application increased (*P*<0.01) populations at Gleadthorpe, again probably due to the presence of worms within the broiler litter itself (Figure 7b). However, the absolute increase was small on the sandy soil at Gleadthorpe (*c*.30 kg/ha, equating to *c*.20 worms/m^2; the majority of which were juvenile, probably because many don't survive to adulthood as the sandy soil at this site is inherently droughty and low in organic matter).

Figure 6. Effect of organic material additions on the population of 'stubby root' nematodes at Gleadthorpe (Site 4, spring 2006).

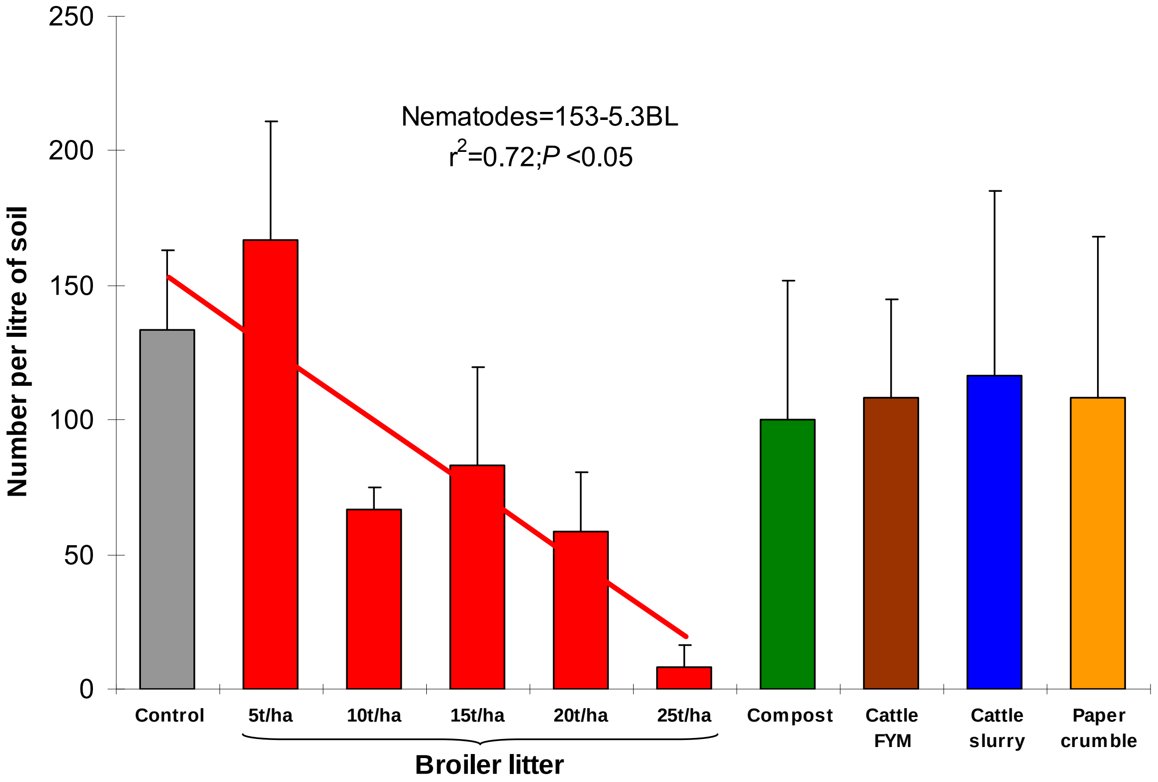
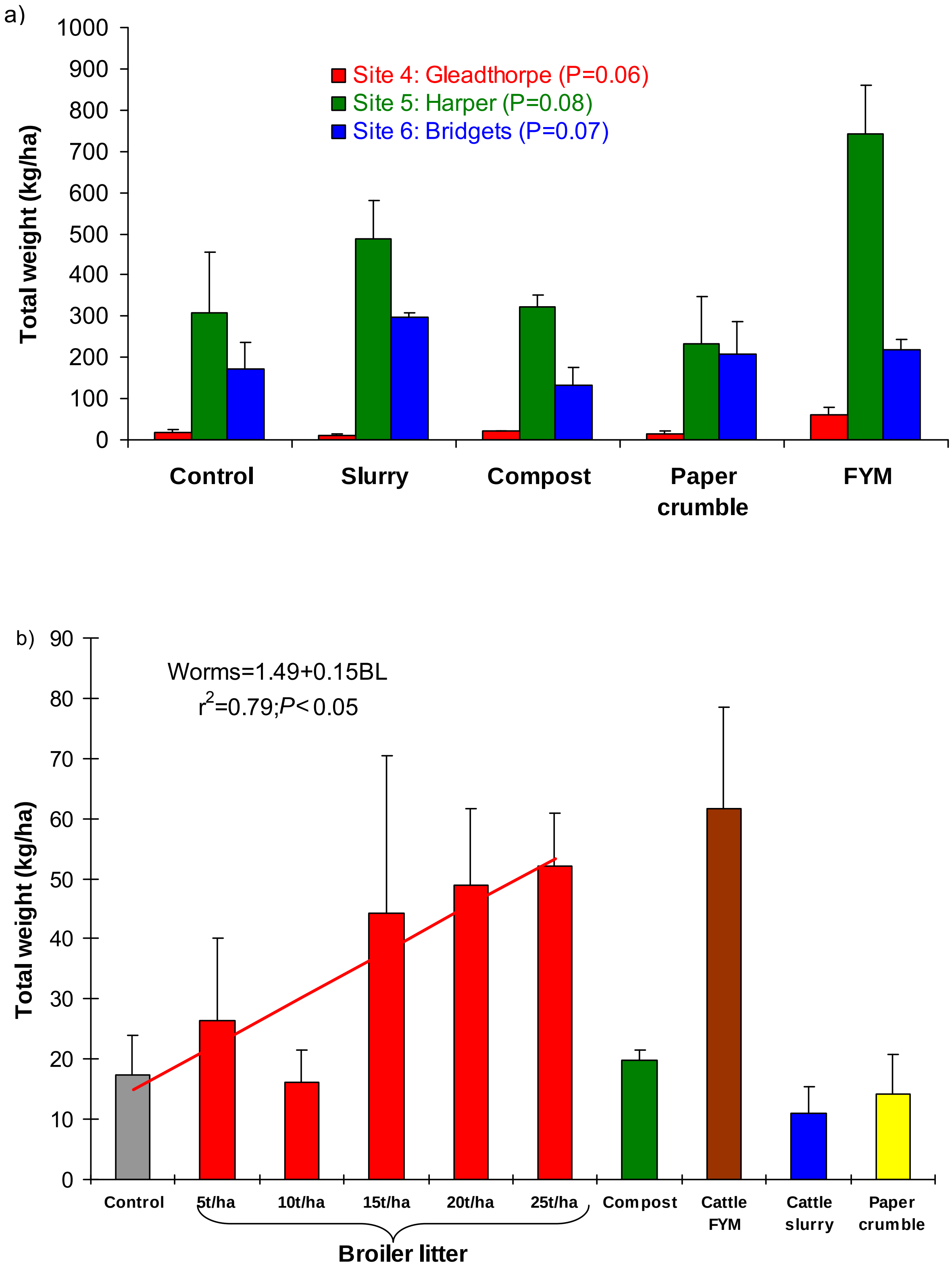


Figure 7. Effect of organic material additions on earthworm populations at a) sites 4-6 and b) site 4 only.



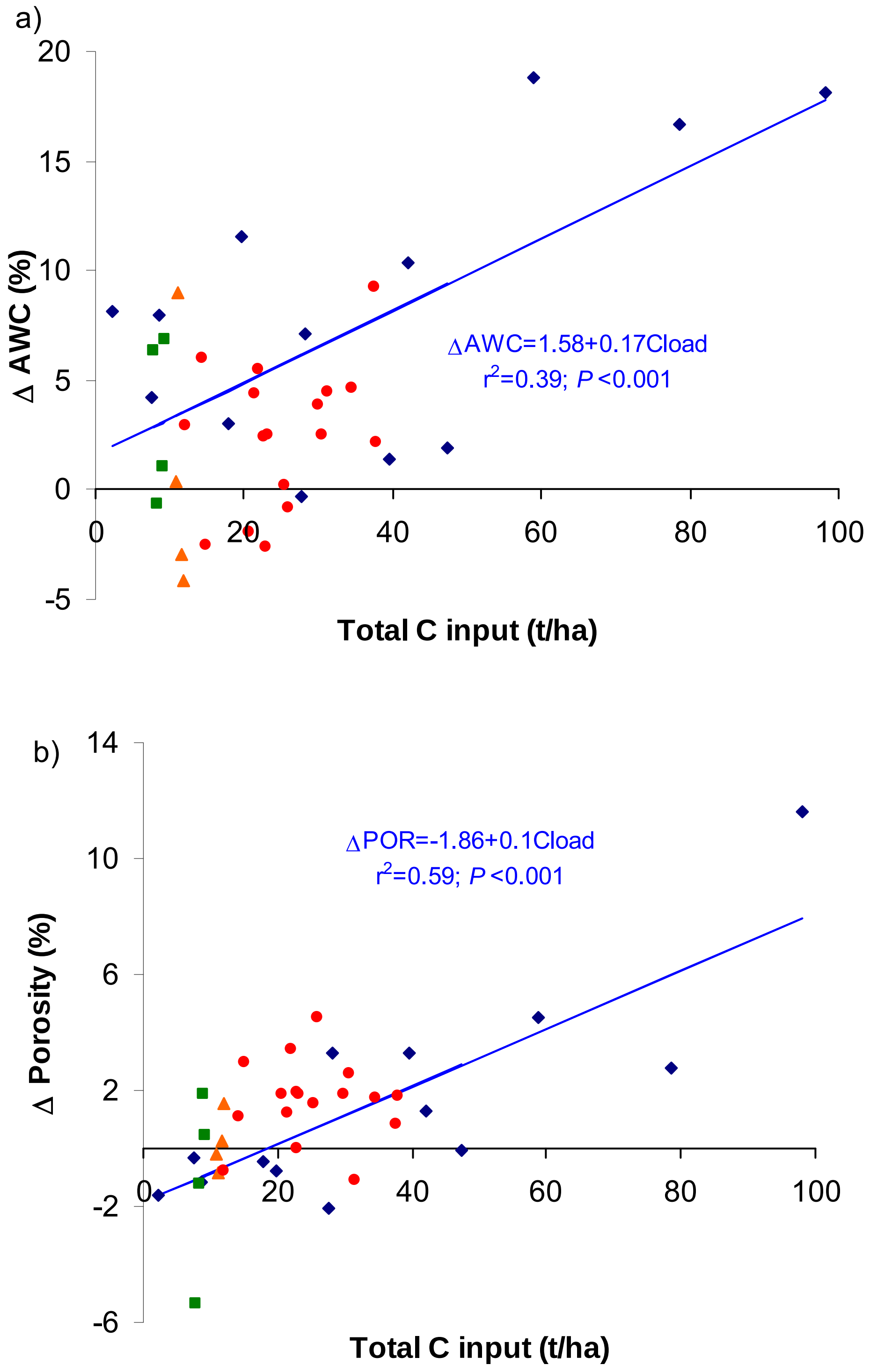
Soil physical properties

The plant available water capacity (AWC) of the topsoils ranged from 12 to 28% on the untreated control treatments at the 7 sites (Appendix 4), and increased by *c*.2% for every 10 t/ha of organic material OC applied (Fig. 8a), but showed no relationship ($P>0.05$) with crop residue OC inputs. There was also a *c*.1% increase in topsoil porosity and *c.*1% decrease in bulk density with every 10 t/ha of organic material OC applied (Figs. 8b&c), but again not with crop residue OC additions. Topsoil porosity ranged from 43 to 64% on the untreated control treatments and bulk density from 0.9 to1.5 g/cm^3. Topsoil physical properties at all sites and treatments are given in Appendix 4, Tables 5 & 6.

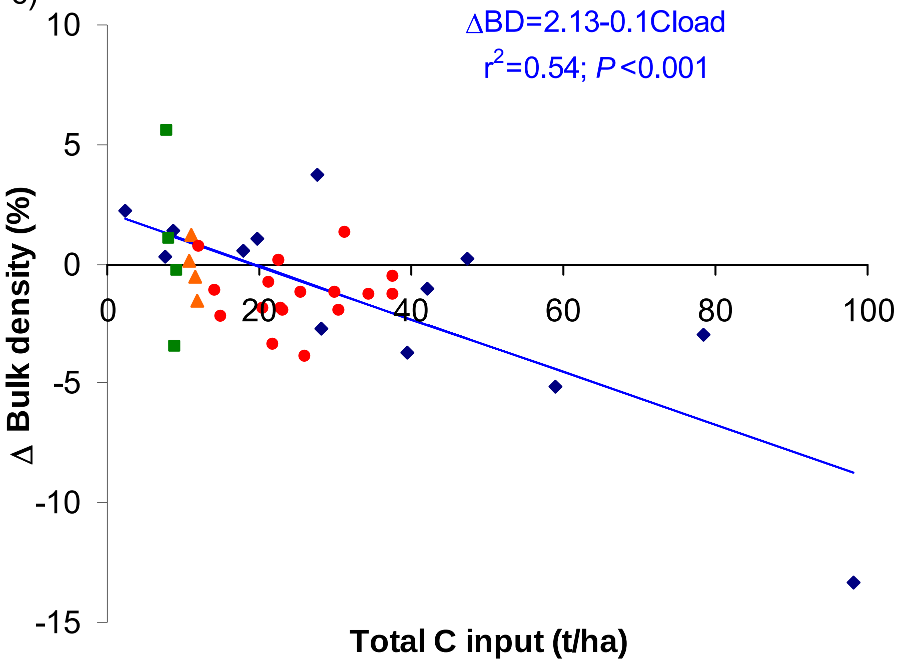
Small (10-17% above the untreated control) but consistent increases in water retention from the application of livestock manures, and to a lesser extent compost (3-11% above the untreated control) and paper crumble (4-14% above the untreated control), were seen across the full range of water potentials (from field capacity, 0.05bar to permanent wilting point, 15bar), particularly on the sandy soils at site 4 (Gleadthorpe; 6% clay) and 5 (Harper Adams; 12% clay), Figure 9. Water held between 0.05 and 2 bar pressure is considered to be the easily available water capacity (EAWC) to plants and was on average 72% of the total plant AWC (range: 52-86%). Changes in EAWC were greater than those measured in total AWC and increased by *c*.3% with every 10 t/ha organic material OC applied (Fig. 8d).

The measured increases in water retention, particularly the EAWC, can have a significant impact on crop yields, water use and consequently farm economics, particularly on low AWC sandy soils where vegetables are grown. Also, the ability of crops to withstand short periods of drought can be improved and the necessity for irrigation water to be applied can be delayed and possibly even reduced. For example, the yield response of potatoes to applied irrigation water on sandy textured soils is *c*.0.25 t/ha/mm (Bailey, 1990). A 10% increase in total plant AWC (e.g. following 50 t/ha OC addition, Fig. 8a) is equivalent to an additional water supply of *c*.5 mm in the top 30 cm of soil. For unirrigated (or under irrigation) potatoes, this ‘additional’ water would result in *c*.1.25 t/ha of extra yield (worth *c*.£125/ha at current prices).

Figure 8. Change in topsoil a) available water capacity (AWC), b) porosity, c) bulk density and d) easily available water capacity (EAWC), with total carbon inputs in the form of ‘organic materials’ (livestock manures (◆), compost (■) and paper crumble (▲)), and crop residues (●). Results are expressed as a percentage difference from the untreated control treatments. Blue line indicates a relationship between the ‘organic material’ OC inputs only.



c)


ΔBD=2.13-0.1Cload
r^2=0.54; *P*<0.001
Δ Bulk density (%)
Total C input (t/ha)
10
5
0
-5
-10
-15
0
20
40
60
80
100

d)

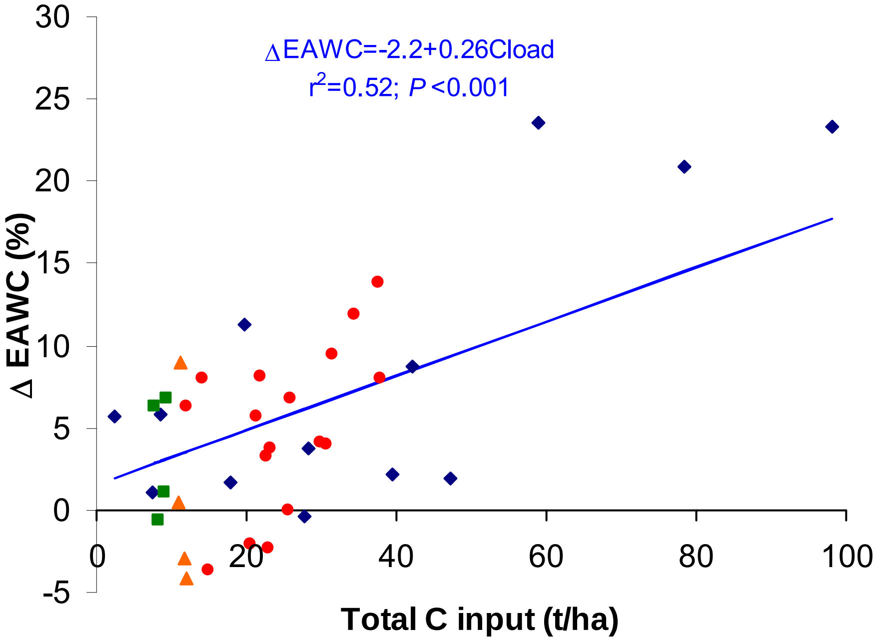
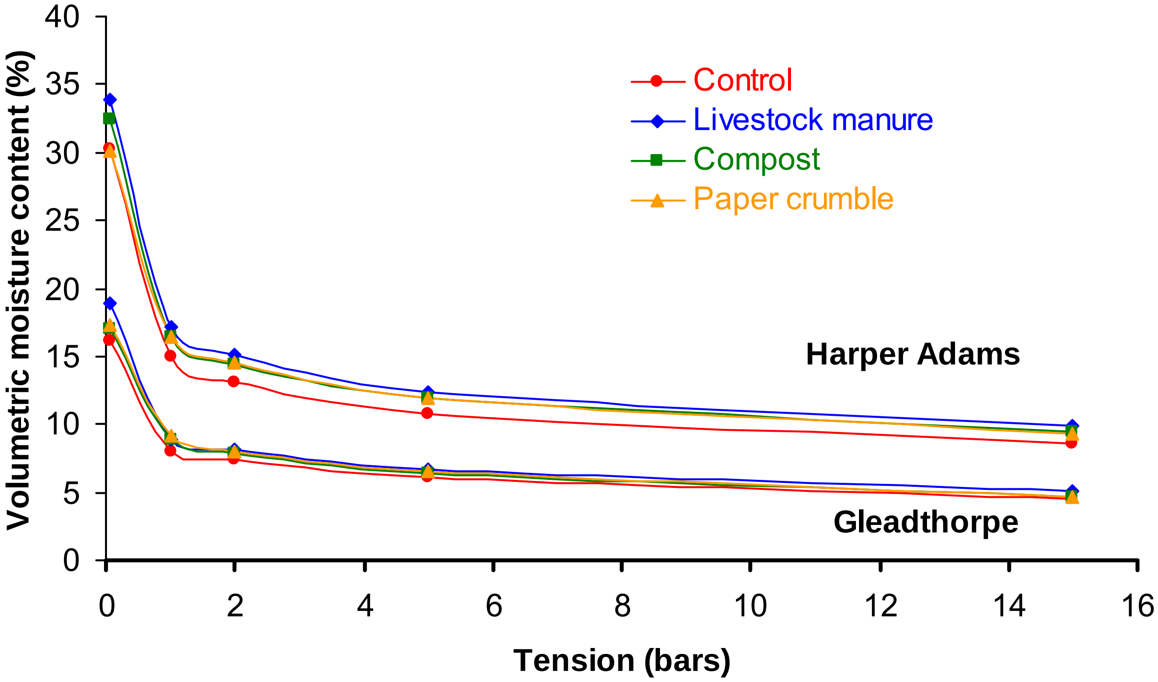

ΔEAWC=-2.2+0.26Cload
r^2=0.52; *P*<0.001
Δ EAWC (%)
Total C input (t/ha)
30
25
20
15
10
5
0
-5
0
20
40
60
80
100

Figure 9. Effect of repeated organic material additions on moisture release curves at Gleadthorpe (site 4) and Harper Adams (site 5).



The OC inputs (both organic materials & crop residues) had no effect (*P*>0.05) on topsoil shear strength which ranged from 11 to 54 kPa on the untreated control treatments, indicating a low to medium degree of consolidation (Anon, 1982; Appendix 4). However, penetration resistance (to 15cm) decreased by *c*.1.5% with every 10 t/ha of organic material and crop residue OC inputs, with no difference (*P*>0.05) due to form of organic input (Fig. 10a).

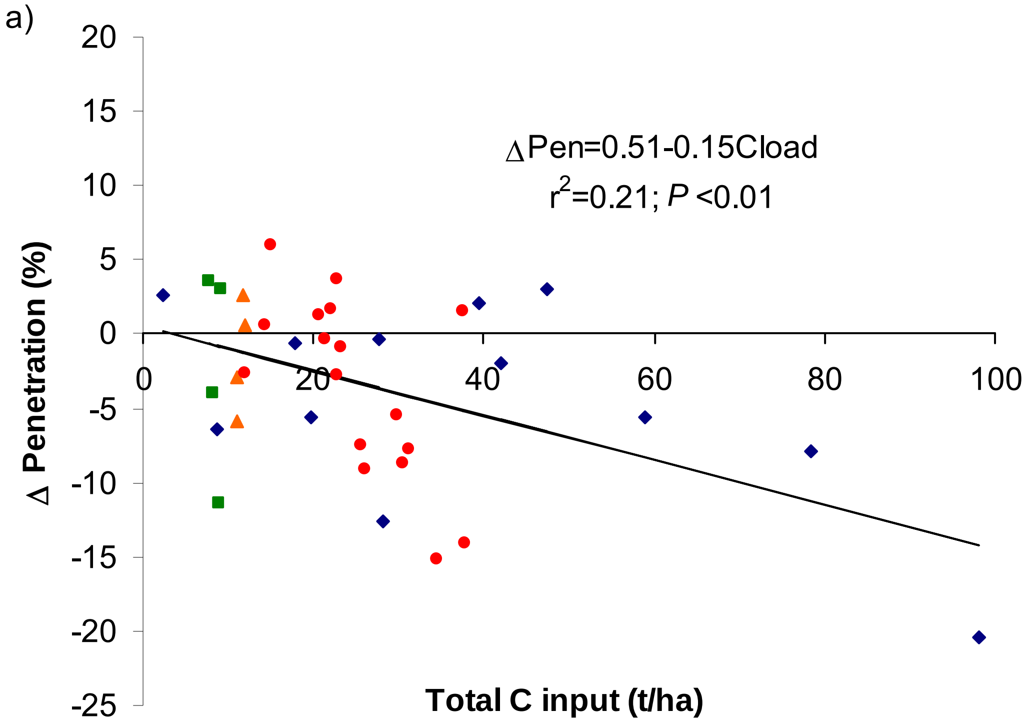
Aggregate stability (as measured by the dispersion ratio method), was not influenced (*P*>0.05) by the OC inputs, with ratios ranging from 4 to 24 on the untreated control treatments, indicating the presence of fairly stable aggregates (Appendix 4; Anon, 1982). The Le Bissonnais technique (Le Bissonnais, 1996) was also used to provide a potentially more sensitive measure of aggregate stability, with the soils subjected to a series of different destabilising treatments (i.e. fast wetting, slow wetting and mechanical energy). However, a relationship was only measured following fast wetting (a measure of the resistance to slaking) and in contrast to the majority of results, greater stability was measured with increasing crop residue OC inputs (Fig. 10b).

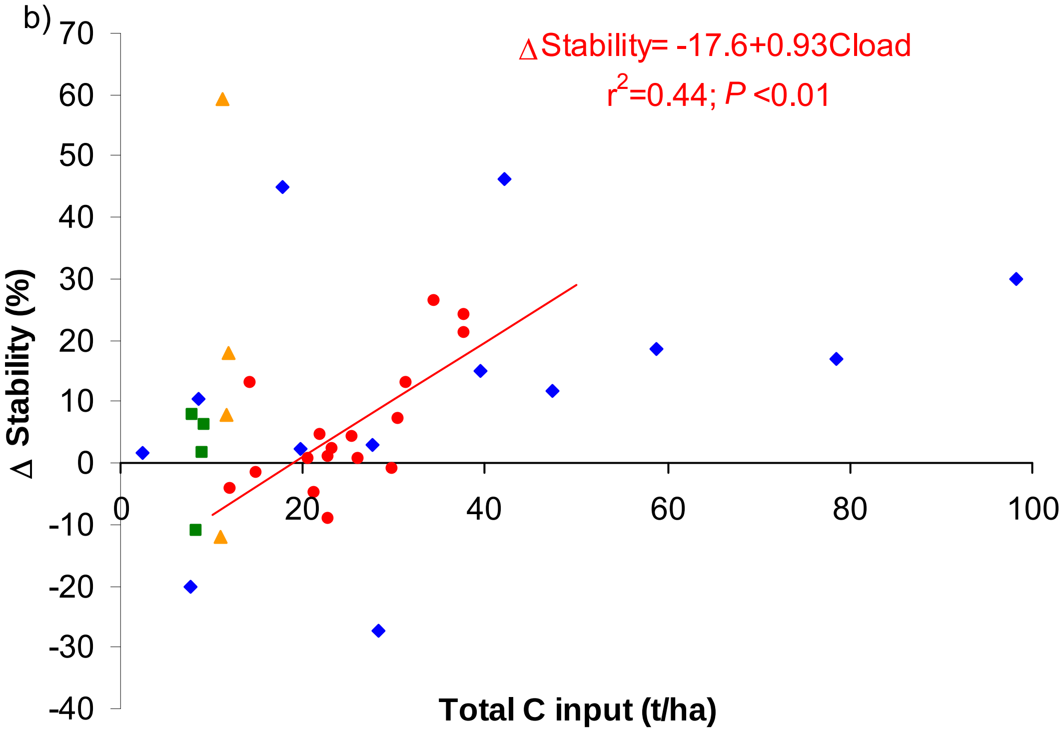
A number of other soil physical properties were measured as part of this study, including:

- structural regeneration by the analysis of cracking patterns (an index of a soils ability to 'reset' itself between seasons and a measure of soil resilience; Preston *et al.,* 1997; 1999);
- water infiltration rates (both in the laboratory on soil aggregates and in the field using double ring infiltrometers);
- measurement of resistance to wind and water erosion (at selected sites);
- field ploughing resistance (at selected sites).

However, there was no consistent effect of OC additions (*P*>0.05) on any of the above soil properties.

Figure 10. Change in topsoil a) penetration resistance and b) aggregate stability following fast wetting, with total carbon inputs in the form of 'organic materials' (livestock manures (◆), compost (■) and paper crumble (▲)), and crop residues (●). Results are expressed as a percentage difference from the untreated control treatments. Black line indicates a relationship between both 'organic material' and crop residue OC inputs, and red line indicates a relationship between the crop residue OC inputs only.





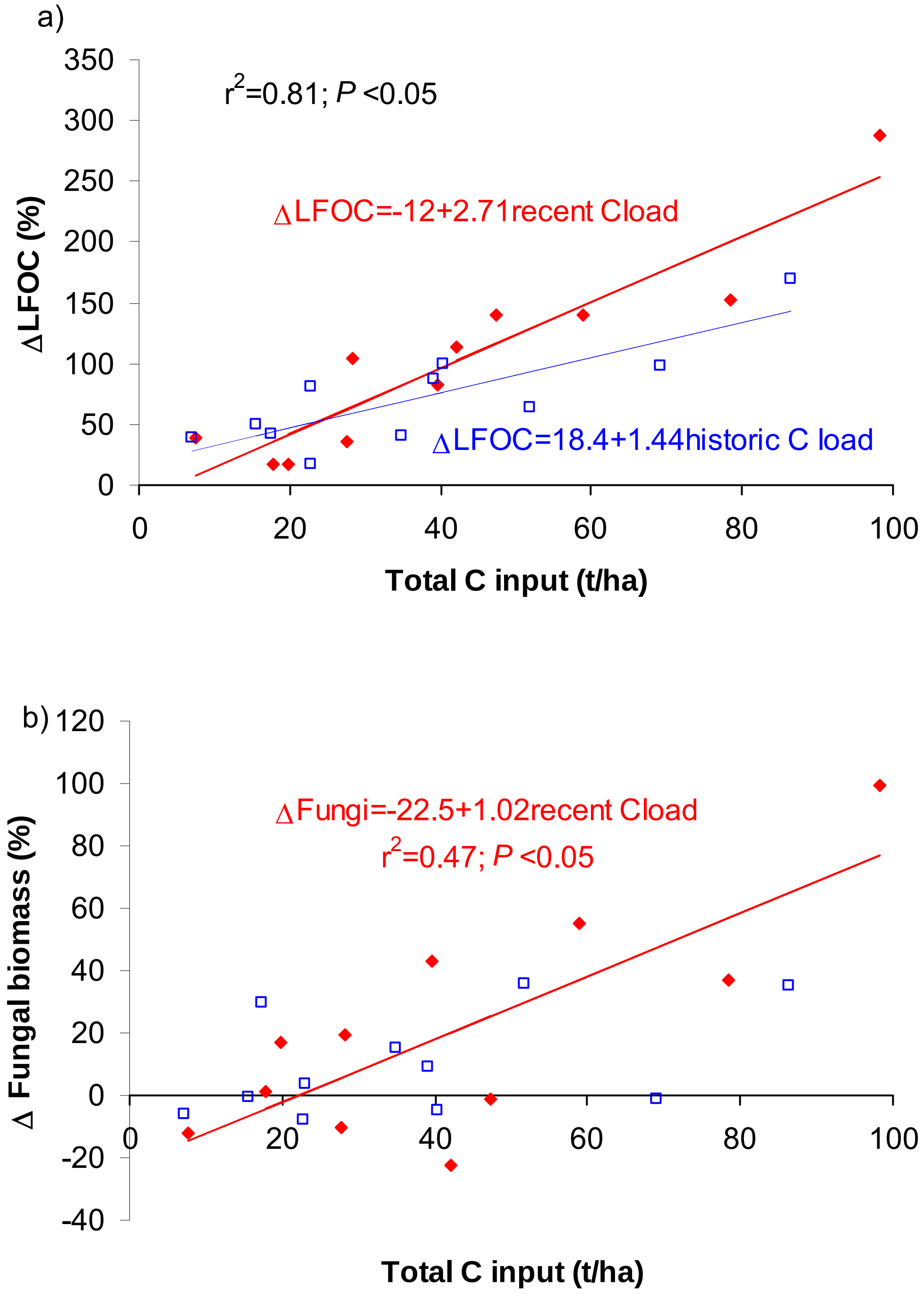
5.4.2 Effect of recent and historic OC additions

Comparison of the effects of ‘recent’ (annual application) and ‘historic’ (last applied 2 years previously) livestock manure OC additions (i.e. excluding the paper crumble and green compost treatments) showed that for the 15 soil properties where there was a relationship with organic material OC loading rates, only 3 showed a different response between the ‘recent’ (fresh) and ‘historic’ additions (Table 5). This indicates that the majority of soil properties were influenced by ***total*** accumulated OC loadings, rather than whether the OC was ‘recent’ or ‘historic’ (i.e. last applied 2 years previously).

The exceptions to this general rule were (based on parallel line fitting):

- Light fraction OC (LFOC); which increased at a greater rate following the ‘recent’ compared with ‘historic’ OC additions (Fig. 11a). This is not surprising as LFOC is a transitional pool of OC between fresh residues and humified stable organic matter (Gregorich *et al.,* 1997; Mahli *et al.,* 2003), largely comprising recent root and crop residue returns as well as partially decomposed organic matter from organic material additions, and is considered to be a labile source of carbon (Loveland *et al.,* 2001).
- Fungal biomass (ergosterol); which *only* responded to the ‘recent’ OC additions (Fig. 11b). As decomposer organisms, fungi typically respond to fresh additions of readily decomposable materials in soils, which can cause a temporary flush in hyphal growth (Tisdall & Oades, 1982). Most high output agricultural systems that rely on manufactured fertiliser inputs tend to be dominated by bacterial populations, which thrive on easily available nutrient sources (i.e. they have low fungal:bacterial ratios; Bardgett *et al.,* 1999). This is compared to more extensive agricultural systems where the decomposition of organic residues and internal nutrient cycling tends to be dominated by fungi (i.e. they have higher fungal:bacterial ratios). As the ‘historic’ treatments and untreated controls had received manufactured fertiliser N, P & K as their sole nutrient sources for at least 2 years prior to sampling, it was not surprising that there was no change in the soil fungal biomass population where livestock manure additions had been with-held, due to the absence of a ‘fresh’ carbon source. However, the apparent lack of response in soil fungi on the ‘historic’ treatments had no impact on the responses measured in other soil properties, such as microbial biomass size and soil physical properties (AWC, porosity, penetration resistance), which responded in a similar manner to both ‘recent’ and ‘historic’ manure OC additions.
- Extractable K; the ‘recent’ OC additions gave rise to a proportional upward shift which was constant across the loading rates. This is not surprising as livestock manures are a valuable source of plant K (90% of manure K is typically readily available for uptake; Anon., 2000), with a typical application of cattle FYM (@ 250 kg/N/ha) supplying *c.*280 kg/ha K and broiler litter (@ 250 kg N/ha) *c.*370 kg/ha K (Anon., 2000; Chambers *et al.,* 1999).

Figure 11. Change in topsoil a) light fraction organic carbon (LFOC), and b) fungal biomass (ergosterol concentrations), with total carbon inputs (◆ 'recent' – applied annually; □ 'historic' – withheld for 2 years). Results are expressed as a percentage difference from the untreated control treatments and relationships were derived from pooled site data. Solid red line indicates a relationship with the 'recent' additions, solid blue line indicates a relationship with 'historic' OC inputs; the single r^2 value for Fig 1a gives a measure of the 'goodness' of fit for fitting 2 lines rather than a single line.



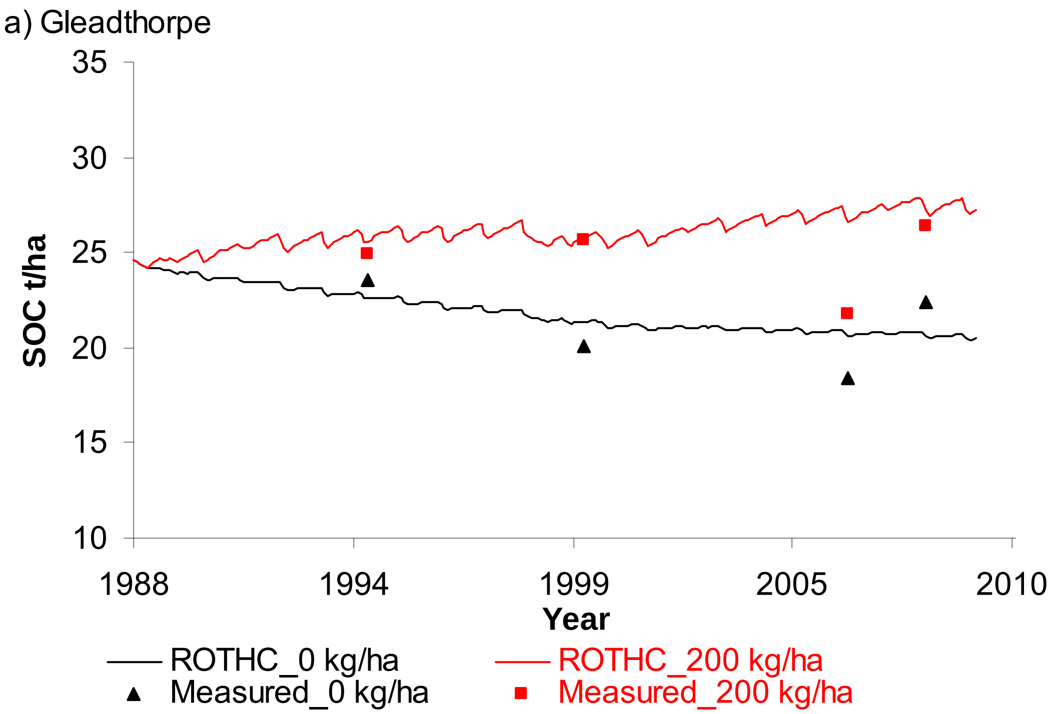
These findings are in contrast to the hypothesis of Loveland *et al.* (2001) who suggested that the 'active' or 'fresh' components of SOC were probably more important in controlling changes in soil properties rather than the accumulated 'stable' SOC pool. Loveland *et al*. (2001) based their hypothesis on the conclusions of Tisdall & Oades (1982) who suggested that aggregate stability may be better related to 'fresh' organic materials, because this fraction was the substrate for the microbial production of organic 'glues' (polysaccharides) and was also a measure of roots and hyphae. However, the organic materials considered were either simple carbon compounds added in laboratory studies (e.g. glucose & cellulose), or crop residues from field studies comparing grass and arable systems. However, in this project we evaluated the effects of *livestock manure* additions, which are typically sources of partially decomposed carbon, and they generally had the same influence on soil properties (particularly soil physical properties) regardless of whether they had been recently (i.e. within 6 months of measurement) or historically (over 2 years old) applied. Clearly, the assumption that manure OC sources will behave similarly to the simple compounds evaluated by Tisdall & Oades (1982) and the associated hypothesis of Loveland *et al.,* (2001) does not appear to be correct. Overall, it was the ***total*** amount of manure OC applied that appeared most important, which (potentially) has a profound impact on soil management advice to increase SOC i.e. *repeated rather than one-off applications are needed to improve soil quality and resilience; where organic material application rates are limited to comply with NVZ rules and COGAP recommendations (i.e. that applications should not exceed 250 kg/ha total N).*.

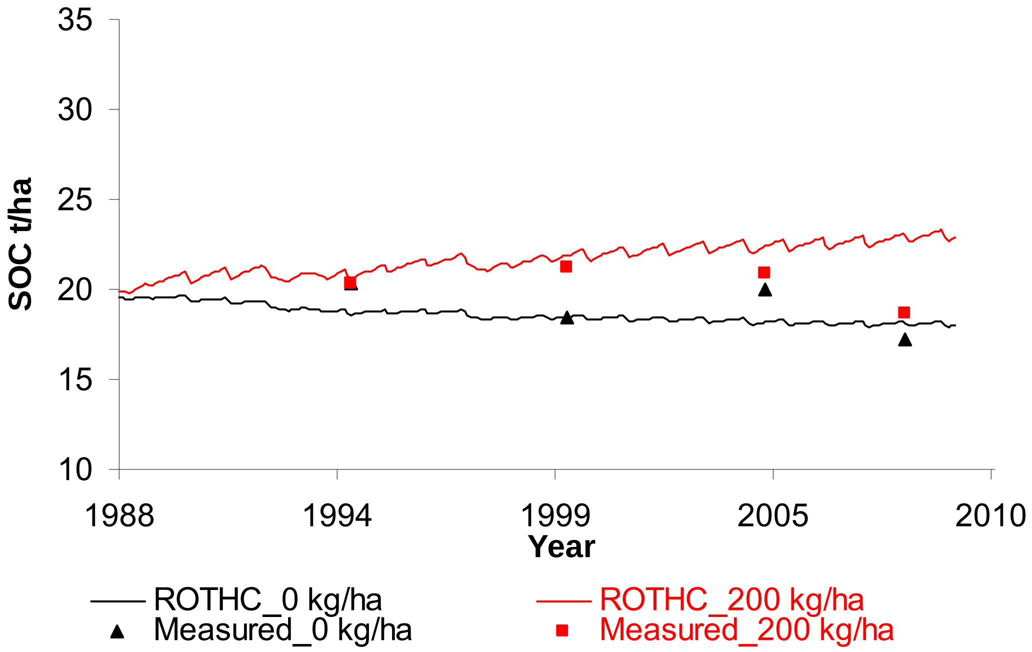
Livestock manure additions have been shown to improve soil fertility and functioning. For example, Leroy *et al*. (2008) measured improvements in aggregate stability and hydraulic conductivity after just 2 years of farm manure additions (albeit supplying *c*.40 t C/ha) to a sandy loam soil in Belgium. Also, Schjonning *et al*. (2007) observed improvements in a number of soil properties important in the development of a good soil tilth (clay dispersibility, length of fungal hyphae, pore size distribution), within 5-6 years of repeated manure applications (as anaerobically digested slurry supplying *c*.0.3 t C/ha/yr) to a sandy loam soil in Denmark. The improvements in soil properties in this study (Section 4.4.1 and Table 5) were first measured after 7-9 years of repeated OC additions, supplying up to 65 t C/ha (Bhogal *et al.,* 2009). Fauci & Dick (1994) in a greenhouse study using soils with different long-term management histories collected from a wheat-fallow rotation in the United States of America, demonstrated that those with a long-term history of organic amendments, such as livestock manure, generally maintained a higher biological activity compared with those receiving manufactured fertilisers, even in the presence of recent amendments. However, recent additions were seen to have a more pronounced effect on soil biological responses. Notably, the microbial biomass showed a comparable response to fresh organic amendments on soils with and without a long-term history of manure additions i.e. the magnitude of the response was the same. Bitman *et al.* (2005) measured increased microbial abundance in a medium textured grassland soil in Canada following 4 years of dairy slurry addition, which persisted for 2 years after applications had ceased. Similarly, Ginting *et al.* (2003) measured elevated microbial biomass and PMN levels in soils following *c*.11 t C/ha of beef manure or compost additions to continuous corn in the United States of America, which persisted for 4 years after applications had ceased. Hence, based on the measurements in this study and data in the wider scientific literature the beneficial effects of livestock manure additions are *likely to persist (and only slowly decline) in soils for several (many) years after applications have ceased;* including biological parameters, such as the microbial biomass, which tend to be more typically characterised by rapid responses to changing management inputs and environmental conditions. Indeed, results from the long-term ‘Hoosfield’ experiment at Rothamsted, clearly demonstrate the legacy of historic FYM applications on SOC contents, which still remain elevated on plots where FYM applications ceased over 100 years ago (relative to a control receiving NPK fertiliser Johnston, 1986).

5.5 Carbon turnover modelling

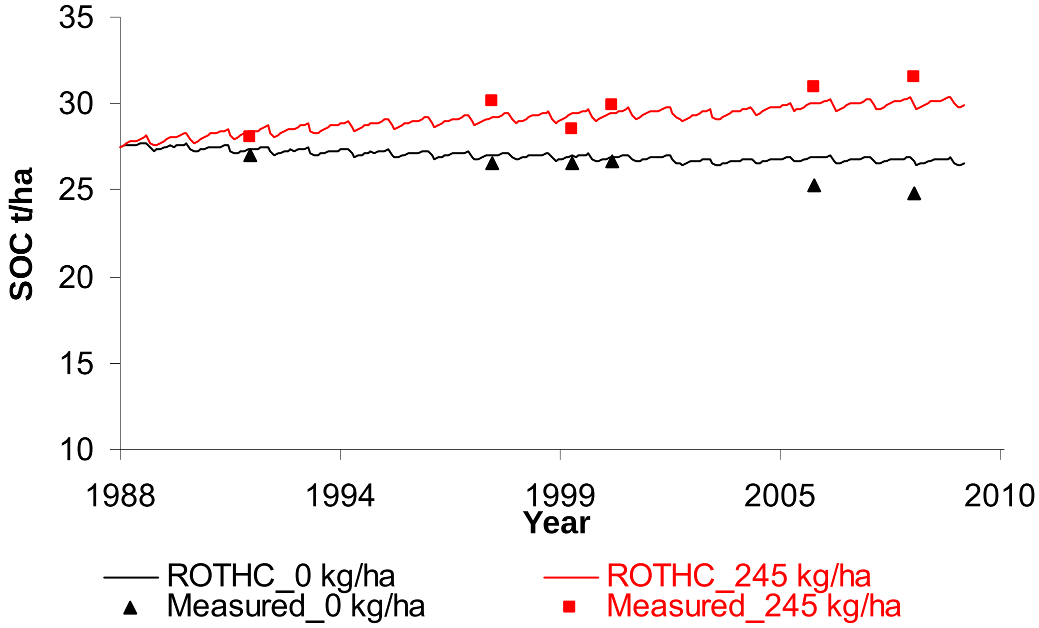
Measured SOC levels at each of the seven sites were compared with predictions of C turnover, using the Rothamsted carbon model (ROTH-C). ROTH-C is a widely-used and well validated model of the soil carbon cycle, which was originally developed and parameterized to model the turnover of organic C in arable topsoils from the Rothamsted Long-term Field Experiments (Jenkinson *et al*. 1987; Jenkinson, 1990; Jenkinson *et al.* 1991; Jenkinson *et al.* 1992; Jenkinson and Coleman, 1994; Coleman & Jenkinson, 1996). Measured changes in topsoil OC during the course of the experiment are given in Appendix 6. The model gave good predictions of changes in SOC at the crop residue sites (Figure 12), using the default assumptions within ROTH-C. Annual applications of 200-245 kg/ha of manufactured N to continuous combinable crops were predicted to increase topsoil SOC by *c*.15, 18 and 10% at Gleadthorpe (5% clay), Morley (13% clay) and Ropsley (27% clay), respectively, over a 30 year period (1988-2018). In contrast, SOC was predicted to decline by *c*.20, 10 and 5% where no manufactured N was applied over a 30 year period at the three crop residue sites, respectively.

Figure 12. ROTH-C predictions of topsoil OC at the crop residue experimental sites: a) Gleadthorpe, b) Morley, and c) Ropsley (using default model assumptions).





b) Morley



c) Ropsley

At the organic material experimental sites, use of the default assumptions within ROTH-C tended to result in an over-estimation of topsoil OC retention. Hence, we used *measured* livestock manure lignin-C and cellulose-C concentrations to adjust the proportions of decomposable plant material (dpm) and resistant plant material (rpm) within the model, with 2% of the solid manure OC allocated to the humus (hum) pool and the manure dissolved OC fraction (DOC) assumed to be removed by leaching. Changing the proportions of decomposable to resistant OC in the applied livestock manures greatly improved predictions compared with using the default assumptions, as shown by an improvement in the 'lack of fit' statistic (Whitmore, 1991) at 3 of the 4 organic material sites (Table 6). For example, at Gleadthorpe (Figure 13a) adjustment of the proportion of dpm to rpm, resulted in a change in the root mean square error of the simulations from 15.7 t C/ha to 8.7 t C/ha.

Table 6 Change in 'lack of fit' statistic following modification of ROTH-C default assumptions at the organic material experimental sites.

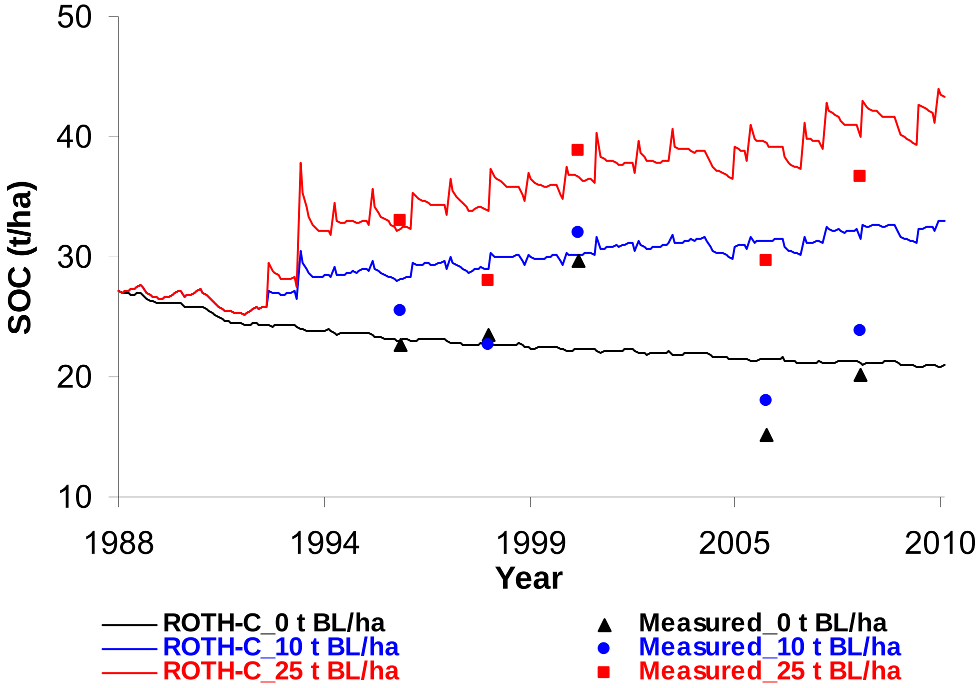
Experimental site	'Lack of fit' statistic	
	Standard ROTH-C	Modified ROTH-C
4. Gleadthorpe	904.6	528.2
5. Harper Adams	268.5	153.5
6. Bridgets	124.5	57.5
7. Terrington	153.9	177.6

Slurry applications were predicted to have little effect on SOC levels, whereas both FYM and broiler litter additions at recommended rates (250 kg N/ha – equating to *c.*40 t/ha FYM and *c.*10 t/ha broiler litter) were predicted to increase SOC levels by 20-30% over a 30 year period (1988-2018). The more recently applied compost and paper crumble additions were not included within this modelling exercise.

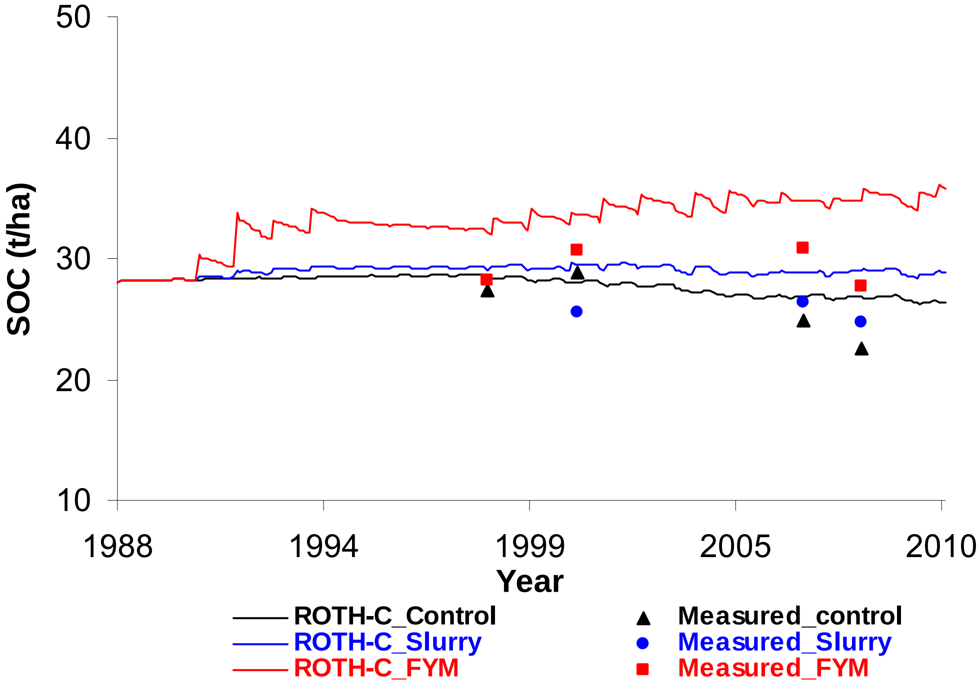
There were SOC measurements at some sites which the model appeared unable to fit, particularly the measurements taken at the two Gleadthorpe sites (1 & 4) in 2006 (Figures 12a & 13a). However, the later measurements taken in 2008 were in good agreement with model predictions. It is therefore probable that the 2006 measurements were 'atypical', but we cannot know this for certain. Accordingly all data have been presented.

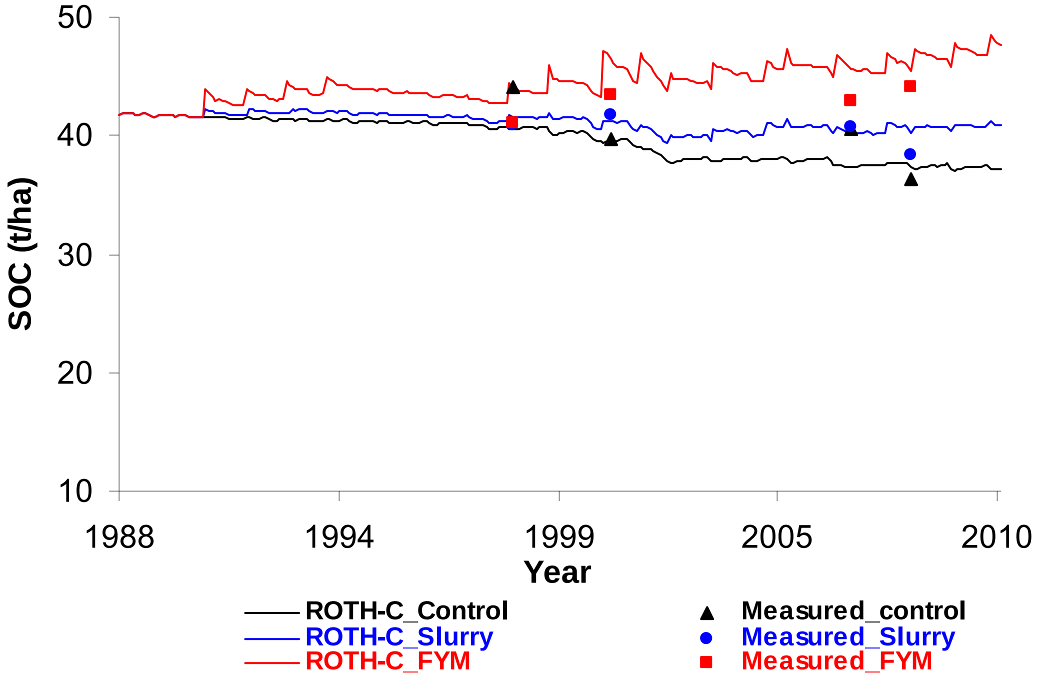
Figure 13. ROTH-C predictions of topsoil OC at the organic material experimental sites: a) Gleadthorpe, b) Harper Adams, c) Bridgets, and d) Terrington (using measured manure C compositions and adjusted dpm:rpm:humus proportions: broiler litter dpm:rpm:humus = 65:27:2, with remaining 6% DOC lost through leaching; FYM dpm:rpm:humus = 56:37:2, with remaining 5% DOC lost through leaching; slurry dpm:rpm:humus = 27:22:0, with remaining 51% DOC lost through leaching)

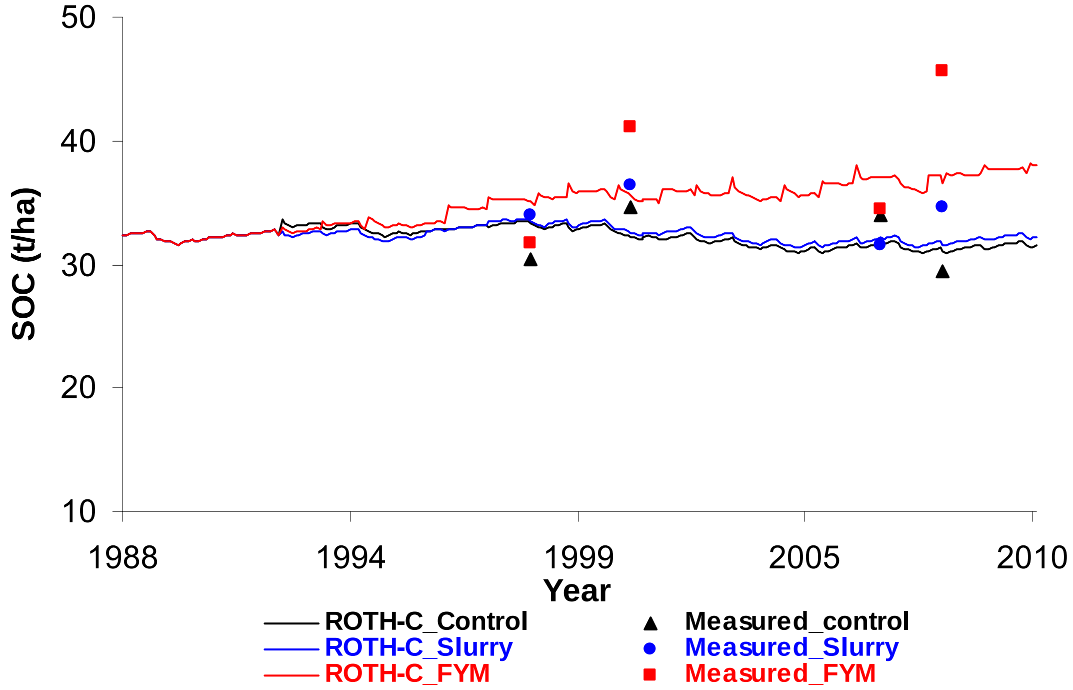
a) Gleadthorpe



b) Harper Adams




c) Bridgets


d) Terrington

6. SUMMARY AND CONCLUSIONS

- The results from this study clearly demonstrate that organic material OC additions produce *measurable changes in a wide range of soil bio-physical and physico-chemical properties and processes*, which are central to the maintenance of soil fertility and functioning (Bhogal *et al.,* 2009). Similar results have been measured in a number of medium to long-term experiments where livestock manures have been applied (e.g. on Broadbalk and Hoosfield at Rothamsted-Johnston *et al.,* 2009; Denmark- Schjonning *et al.,* 1994, 2007; as well as a number of international studies reviewed by Haynes & Naidu, 1998 and Edmeades, 2003). There have been relatively few experiments assessing the effects of repeated compost and paper crumble additions, although increases in SOC, pH and biological properties etc. have been measured (Bhogal & Chambers, 2009; Rato Nunes *et al.*, 2008).

- Organic C inputs in the form of livestock manures (i.e. FYM, slurry and broiler litter) had the *greatest influence* on measured soil processes and properties. In comparison, there were relatively few changes resulting from crop residue OC inputs. Soil chemical (e.g. SOC, LFOC, extractable P, K, Mg) and biological (e.g. microbial biomass, fungal biomass, potentially mineralisable N) properties were the most responsive to OC additions, but a large number of soil physical properties (e.g. shear strength, aggregate stability, infiltration rates, plough resistance etc.) were un-affected. Compost and paper crumble had only been applied to the organic material experimental sites for 2-3 years prior to sampling and therefore had relatively low OC loading rates and associated small effects.

- Small (10-17% above the untreated control) but consistent increases in water retention from the application of livestock manures, and to a lesser extent compost (3-11% above the untreated control) and paper crumble (4-14% above the untreated control), were seen across the full range of water potentials (from field capacity at 0.05bar to permanent wilting point at 15bar), particularly on the sandy soils at Gleadthorpe (6% clay) and Harper Adams (12% clay). Water held between 0.05 and 2 bar tension is considered to be the easily available water capacity (EAWC) to plants and was on average 72% of the total plant AWC. The measured increases in water retention, particularly the EAWC, can have a significant impact on crop yields, water use and consequently farm economics, particularly on low AWC sandy soils where vegetables are grown. The measured 10% increase in total plant AWC (following 50 t/ha OC addition) is equivalent to an additional water supply of *c.*5 mm in the top 30 cm of soil. For unirrigated (or under irrigation) potatoes, this ‘additional’ water was estimated to result in *c.*1.25 t/ha of extra yield (worth *c.*£125/ha at current prices).

- Based on the *body of evidence* from the range of assays undertaken at the organic material experimental sites:
  - changes in soil *physical* properties (e.g. EAWC/AWC, porosity, bulk density and penetration resistance etc) were largely a result of physico-chemical linkages between SOC and soil particles, which changed the physical architecture of the soil matrix, resulting in the soil being more porous and lower in strength, and having improved water retention properties.

- increases in soil *biological* properties (i.e. microbial and fungal biomass size, potentially mineralisable N) were largely the result of bio-chemical linkages between SOC (plus LFOC and total N) and the soil microbial community.
- changes in soil *chemical* properties (i.e. cation exchange capacity, OC, total N and extractable nutrients) were largely a result of the organic material additions *per se*.

- Characterisation of the organic material additions according to their carbon composition (i.e. lignin-resistant, and cellulose-decomposable C) proved particularly valuable to the ROTH-C model predictions of soil C turnover at the organic material experimental sites, where *measured* lignin and cellulose concentrations were used to adjust the proportions of easily decomposable to resistant OC in the model. This greatly improved the prediction of SOC turnover at these sites, which were previously over-estimated using the default assumptions within the model. This is an *important advance* in our understanding of long-term soil carbon storage where organic materials are applied.

- Significant improvements in soil quality and functioning were measured following repeated additions of livestock manures that persisted for at least 2 years following the cessation of applications. Overall, it was the total accumulated livestock manure OC load that had the greatest influence on soil properties and functioning, regardless of whether the OC source was ‘fresh’ (i.e. recently applied) or ‘historic’ (over 2 years old), which was the case for 12 of the 15 relationships. The only exceptions to this general rule were shown by light fraction OC, fungal biomass and extractable K. These findings are in contrast to the hypothesis of Loveland *et al*. (2001) who suggested that the ‘active’ or ‘fresh’ components of SOC were probably more important in controlling changes in soil properties, rather than the accumulated ‘stable’ SOC pools. This finding (potentially) has a profound impact on soil management advice to increase SOC *i.e. repeated applications are needed to improve soil quality and resilience, within the bounds of environmental legislation (e.g. NVZ/COGAP).*

7. FUTURE WORK

The SOIL-*QC* experimental platforms provide a *unique resource* where the effects of contrasting organic material inputs on soil quality and fertility can be studied, as a result of past organic material (e.g. livestock manure, paper crumble and green compost) and crop residue additions. They have also provided valuable scientific underpinning data to a number of other Defra projects (see Section 10).

There are a number of other scientific opportunities that arise as a result of their existence, viz:

- The sites provide an opportunity to quantify the influence of OC additions on the delivery of soil 'ecosystem services', especially their role in *flood mitigation* (water retention and infiltration), *carbon storage* and *erosion control*, as well as food and fibre production.
- The conventional (widely held) view in the scientific community is that the benefits of OC additions to soil functioning are principally derived from the fresh OC inputs (rather than the accumulated total C load), which is contrary to the results of this study. Hence, there would be merit in repeating the comparison of recent (i.e. exposed) *vs*. historic (i.e. protected) OC additions to provide further clarification and understanding of the processes involved, and to underpin *future soil management practice advice* to increase SOC storage and soil quality.
- There would be benefit in introducing *additional organic material treatments* (e.g. digestate, green/food compost, biochar) at the organic manure experimental sites, to complement the existing organic material additions.
- The sites provide a resource to study the effects on *nitrous oxide emissions* of contrasting cultivation systems (e.g. reduced tillage *vs*. ploughing) at a range of manufactured fertiliser N application rates.
- The sites could be used to monitor and measure long-term changes in *SOC levels* and properties - periodic SOC measurements now date back for more than 10 years at all of the sites. Moreover, the established plots could act as *reference sites* (e.g. for assessing SOC changes on sensitive soil types), as part of a tiered soil monitoring framework to assess trends in SOC storage and their impact on soil quality.

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10. KNOWLEDGE TRANSFER

Publications:

Bhogal, A. Nicholson, F.A., Young, I., Whitmore, A.P. & Chambers, B.J. (Submitted). Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality. Paper submitted to a special issue of the European Journal of Soil Science. Proceedings of the Organic Matters Conference, held at Rothamsted Research, June 2009.

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Data from the SOIL-QC experimental sites have provided valuable scientific underpinning data for the following projects:

Defra project SP0561: The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.

EA project SC050054: Road Testing of ‘Trigger Values’ for Assessing Site Specific Soil Quality.

WRAP “Compost Use in Agriculture: Training for Crop Consultants II” workshops (11 workshops were held between November 2007 and February 2008 and were attended by more than 170 people).

Appendices

Appendix 1. Crop yields harvest years 2004-2008

Table 1. Crop yields and crop residue OC returns at the crop residue experimental sites (sites 1-3), 2004-2008

N applied (kg/ha)	Grain/seed yield (t/ha)[a]					Crop residue C returns (t/ha)[b]				
	03/04	04/05	05/06	06/07	07/08	03/04	04/05	05/06	06/07	07/08
1. Gleadthorpe[c]	WW	WOSR[e]	WW	WW	WOSR					
0	2.18	0.70	2.47	2.08	1.27	1.05	0.76	1.14	1.12	1.51
50	4.48	1.16	4.07	3.70	2.31	2.22	1.27	2.06	1.76	2.75
100	6.07	1.69	5.41	4.84	3.06	2.85	1.84	2.67	2.03	3.64
150	6.86	1.80	5.18	4.58	3.38	2.89	1.97	2.53	1.93	4.02
200	6.70	1.79	5.16	5.71	3.29	3.01	1.95	2.83	2.28	3.92
250	6.44	2.06	4.80	5.45	3.15	3.06	2.25	2.73	2.14	3.74
P[d]	*<0.05*	*<0.01*	*ns*	*<0.05*	*<0.05*	*<0.05*	*<0.01*	*<0.05*	*<0.05*	*<0.05*
2. Morley[c]	WW	WW	WW	WW	WW					
0	3.31	2.40	4.24	2.23	4.16	1.09	0.84	1.69	1.18	1.42
50	5.40	3.79	6.05	4.12	6.61	2.08	1.37	2.34	1.55	2.38
100	6.31	4.93	8.08	5.71	8.26	2.21	1.79	3.05	2.13	2.82
150	8.41	5.52	9.11	6.37	9.49	2.77	1.89	3.28	2.22	3.03
200	7.92	6.17	9.85	7.51	10.98	2.67	2.14	3.48	2.48	3.14
250	9.32	6.46	10.30	7.82	10.77	3.30	2.17	3.63	2.39	3.31
P[d]	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.05*
3. Ropsley[c]	WW	WW	WW	WW	WW					
0	2.78	1.48	2.47	1.86	3.03	1.21	0.63	1.04	0.65	2.12
35	4.69	3.14	4.37	3.00	5.55	1.86	1.30	1.98	0.87	2.42
70	5.89	5.18	6.44	3.65	7.12	2.24	2.01	2.65	1.18	3.40
105	6.28	5.52	7.61	4.39	8.35	2.12	2.00	2.97	1.26	3.43
140	7.25	6.50	8.17	4.54	9.12	2.36	2.23	3.08	1.31	3.55
175	7.68	6.53	8.76	5.07	9.80	2.35	2.39	3.31	1.48	3.84
210	8.14	6.57	9.76	5.02	10.31	2.54	2.26	3.89	1.60	4.10
245	7.77	7.80	9.91	5.93	10.87	2.52	2.77	3.73	1.81	4.66
P[d]	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.01*	*<0.01*	*<0.001*	*<0.001*	*<0.001*

[a] Grain yield at 85% DM, oilseed rape seed yield at 91% DM.

[b] Crop residue C returns include straw, stubble and root material. These were estimated from the total above ground biomass production (grain + straw) assuming half of the non-grain biomass was returned in the stubble and chaff (Anon., 1997), that root dry matter production was equivalent to *c*.8% of shoot dry matter (Gregory *et al.,* 1978) and that all dry matter contained 40% OC.

[c] Cropping: WW: winter wheat; WOSR: winter oilseed rape

[d] Statistics by regression analysis

[e] Higher N rates applied to WOSR at Gleadthorpe in 2004/05: 0-300 kg/ha in 60 kg/ha increments

Table 2. Crop yields at the organic material experimental sites (sites 4-7), harvest years 2004-2008.

Site	Treatment[a]	Grain yield (t/ha @ 85% DM)[b]				
		03/04	04/05	05/06	06/07	07/08
4. Gleadthorpe[c]	Broiler litter (t/ha):	WB	SOSR	WW	SOSR	WW
	0	4.88	0.66	2.98	0.22	8.35
	5	5.69	0.46	3.84	0.44	8.33
	10	6.41	0.74	3.51	0.71	8.61
	15	6.18	0.46	4.38	0.63	9.72
	20	6.20	0.35	4.13	0.53	8.81
	25	6.66	0.98	3.80	1.00	8.41
REGRESSION	*P*	$P<0.05$	*ns*	*ns*	<0.05	*ns*
	Cattle FYM	nd	0.24	4.44	0.39	8.65
	Cattle slurry	nd	0.36	4.28	0.51	7.39
	Compost	nd	0.35	3.85	0.33	8.72
	Paper crumble	nd	0.23	3.72	0.46	6.61
ANOVA	*P*		<0.05	*ns*	*ns*	*ns*
5. Harper Adams[c]		SOSR[d]	SB[e]	WB[f]	WOSR[d]	WO
	Untreated	nd	4.45	6.66	0.44	5.99
	Cattle FYM	nd	4.24	7.54	0.67	6.12
	Cattle slurry	nd	5.44	7.31	0.96	6.50
	Compost	nd	5.08	6.20	0.89	5.96
	Paper crumble	nd	2.51	5.54	1.41	5.99
ANOVA[d]	*P*		<0.01	<0.05	*ns*	*ns*
6. Bridgets[c]		WW	WOSR	WW	SB	WOSR
	Untreated	8.96	2.95	11.15	8.23	4.23
	Cattle FYM	10.32	3.48	11.22	7.11	5.53
	Cattle slurry	8.90	3.75	11.36	8.34	5.44
	Compost	nd	2.65	10.16	7.57	5.06
	Paper crumble	nd	2.41	11.24	8.41	4.66
ANOVA	*P*	*ns*	*ns*	*ns*	*ns*	<0.05
7. Terrington[c]		SOSR	SW	WW	WOSR	SB
	Untreated	1.52	6.40	6.32	3.44	5.90
	Pig FYM	1.57	6.36	8.55	3.04	5.96
	Pig slurry	1.35	6.30	7.85	3.01	8.03
	Compost	nd	6.03	6.77	3.31	7.05
	Paper crumble	nd	5.98	7.80	3.71	6.45
ANOVA	*P*	*ns*	*ns*	<0.05	*ns*	*ns*

[a] New organic material treatments (compost, paper crumble at all sites; cattle FYM and slurry at Gleadthorpe) first applied post harvest 2004.

[b] Grain yield at 85% DM, oilseed rape seed yield at 91% DM.

[c] Cropping: WB=Winter barley; WW= Winter wheat; SOSR= spring oilseed rape; SB= spring barley; WOSR= winter oilseed rape; WO= Winter oats; SW= Spring wheat

[d] Bad weather prevented harvesting on a plot by plot basis in 2004; heavy rainfall in 2007 caused substantial damage to the oilseed rape crop, yields should therefore be treated with caution.

[e] The crop requirement for additional manufactured N on the organic material plots at Harper Adams in 2005 was deemed to be ‘small’ due to late drilling of the spring barley crop (23/3/05) and hence no additional N fertiliser was applied to these plots (86 kg/ha N applied to the untreated control on 9/5/05). This had no detrimental effect on final yields, except for the paper crumble treatment where the yield was significantly lower than on the livestock manure treatments.

[f] The main manufactured N dressing was delayed (25/5/06) at Harper Adams in 2006 so application rates were halved to account for a lower potential N uptake. This had no detrimental effect on final yields, except for the paper crumble treatment where the yield was significantly lower than on the livestock manure treatments.

Appendix 2. Methods

Measurement of plough resistance (sites 3 & 4)

Measurement of the specific draught (draught force divided by the cross sectional area of soil moved, kPa) of a plough provides a continuous measure of soil strength. The specific draught force (plough resistance) was measured at sites 3 (Ropsley crop residue experiment) and site 4 (Gleadthorpe organic material experiment), where organic C inputs had been the greatest. However, due to the layout and limited length of the experimental plots at these sites use of a mouldboard plough to measure soil strength on individual plots was rather impractical. An alternative technique reported by Sharifi *et al* (2007) was used. This approach uses a series of instrumented load sensors attached to the leading edge of a vertical tine. These are designed to measure the resistance of each individual soil engaging component (flap) at a number of different depths. The authors showed this technique to be sufficiently sensitive to enable increases in soil strength to be measured brought about by the passage of vehicles of increasing weight or where tyres were used at higher inflation pressures.

For this experiment the tine described by Sharifi *et al* (2007) was operated at 25 cm depth and soil resistance was measured at 15 and 20 cm depth at Gleadthorpe and at 10, 15, 20 and 25 cm at Ropsley. Precise working depth was maintained using a combination of depth wheels and a full width packer roller. Data from the individual sensors was recorded at 100 Hz and stored on a laptop PC mounted in the tractor cab. Typical run durations per plot were 10 s at Gleadthorpe and up to 30 s at Ropsley.

Measurement of resistance to wind erosion (site 4 only)

This method measured the susceptibility of soils to wind erosion. It was performed at site 4 (Gleadthorpe) which is a light sandy loam susceptible to wind erosion, but also the most responsive to organic carbon additions (Defra project SP0501).

Measurements were taken following ploughing & pressing and immediately following drilling on a dry day in spring 2006 (i.e. when soils were most susceptible to wind erosion), using wind tunnels, based on the design developed by Lockyer (1984). Each wind tunnel consists of two parts; a transparent polycarbonate canopy (0.5 m x 0.25 m) which covers the plot area, and a stainless steel duct housing a fan which can either draw or expel air through the canopy (in this case the fans were set to expel air out of the canopy) at a speed of 1 m/s. One wind tunnel was placed on each replicate plot of the control, 10 t/ha broiler litter treatment and 25 t/ha broiler litter treatment. A particle trap was placed flush with the soil surface at the opening of the canopy (which was partially sealed in order to direct any soil particles into the trap). Any soil blown into the trap over a 15 minute period was collected and weighed to give a measure of the susceptibility of the soils to wind erosion (g/min). An anemometer was placed at ground level to record the wind speed, which was on average 4.6 m/s during the course of testing.

Measurement of resistance to water erosion (sites 1 & 4 only)

A mobile rainfall simulator based on a design by Morin, as described by Grierson & Oades (1977) was used to measure resistance to water erosion at sites 1 & 4 (Gleadthorpe crop residue and organic material experimental sites). These sites were selected as they are particularly susceptible to erosion. Measurements were made of time to, and quantity of, runoff, fragmentation (particle size distribution) of the surface layer and changes in hydraulic conductivity (infiltration). Additionally, critical shear stress was measured using a cohesive shear meter.

The simulator is built on a road trailer and contains two 200 litre water storage tanks, a pump and a nozzle. For the purpose of this experiment the trailer was fitted with a frame and three-point linkage to allow it to be picked up by a tractor. This enabled the simulator to be operated from existing tramlines thus reducing the damage done by wheels to experimental plots. A nozzle producing raindrop-sized droplets, travelling at realistic speeds produces excessive rainfall intensities. Thus for this design of rainfall simulator a revolving metal disc intercepts most of the water from the nozzle and recycles it back into the storage tanks. An adjustable slot in the metal disc, revolving at 40 rpm, allows a proportion of the nozzle output to reach the soil, giving mean rainfall intensities of 12 – 100 mm/h. For this experiment, the rainfall simulator was used to apply a series of standard storms with an intensity of 44.5 mm/hr and duration of 20 minutes on selected plots at sites 1 & 4. This storm intensity, although rather high, was not unrealistic for UK conditions e.g. an intensity of 47 mm h^{-1} with a10 min duration has a probable 1 year return period in Bedfordshire, (data from NERC Flood statistics report 1975). A relatively high storm intensity was chosen to be sure that runoff would be generated in a reasonable time.

Simulated rainfall impacts on the soil surface within and around a 1 m^2 metal frame driven into the surface. Where there is a slope (e.g. site 1) any runoff flows down to one end of the frame and into a sump. From here it is drawn off by means of a vacuum pump into a 1.0 litre-measuring cylinder. On soils with a limited slope (e.g. site 4), time to puddling was recorded and the puddled water adjacent to the metal frame was collected using a wand arrangement connected via the measuring cylinder to the vacuum pump. The volume of runoff collected was recorded at different time intervals during the storm. Water and sediment were collected each time the measuring cylinder was filled. The concentration of sediment collected in the runoff water was determined by oven drying and weighing the material remaining. These values were averaged for the first 5 litres of runoff collected. On selected samples the size distribution of this sediment was determined using a combination of sieving and sedimentation.

Intact soil cores (75mm diameter) were also collected from the upper 5 mm of soil, both before and following the storm. Samples were air dried and gently sieved through the following sieves in turn: 5.00, 2.00, 1.00, 0.50, 0.20, 0.10 and 0.06 mm. From this data the weight of fine material (the combined silt and clay fraction <0.06 mm) and the mean weight diameter (MWD) was recorded in order to assess the level of fragmentation of the surface layer.

Following rain and when runoff occurs, soil erosion begins only once a critical shear stress ($\tau_{0\,\square\mathrm{crt}}$) exerted by the flowing water is exceeded. Critical shear stress was determined using a cohesive shear meter (CSM). Here a submerged vertical jet of water is used to erode the soil surface within a water-filled, 30 mm diameter chamber pushed into the soil surface. An infrared light path traverses the chamber 10 mm above the soil surface. The velocity of the jet pulse is then increased systematically through time. Bed erosion is inferred from the drop in the transmission of infrared light across the chamber caused by the suspension of sediment. Loss in transmission and jet pressure are logged and both critical shear stress and a semi-quantitative index of the erosion rate are also determined. This later term, called the suspension index (s_i) by Tolhurst *et al*. (1999) was calculated from the relative increase in suspended sediment concentration with increasing water-jet velocity. This latter term is an indicator of how rapidly the sediment bed fails.

A typical output from the CSM represents a drop in transmission plotted against increasing stress and can be described by a logistic curve. Here we take the onset of erosion, or critical shear stress ($\tau_{0\,\mathrm{crt}}$) as occurring at the point of maximum curvature when light transmission is just starting to decrease. Suspension index (s_i) is represented by the gradient of the tangent at the point of inflection. Low (and slightly negative) values of $\tau_{0\,\mathrm{crt}}$ indicate that erosion is likely to occur immediately there is any runoff, whereas higher values imply a more resistant surface where increasing surface flow rates need to occur before the critical shear stress is reached. Similarly, low (negative) s_i vales represent a progressive onset of erosion in contrast to higher (more negative) values where there is likely to be a rapid soil loss as soon as $\tau_{0\,\mathrm{crt}}$ is exceeded.

Appendix 3. Organic material composition

Table 1. Cattle & pig FYM (average of 5 annual applications, 2004-2008, with standard error in italics). Results expressed on a fresh weight basis unless otherwise stated.

Site	Gleadthorpe		Harper Adams		Bridgets		Terrington (pig)		Mean	
Application rate (t/ha)	43.4		40.8		38.8		35.1		39.5	*1.75*
Dry matter (%)	31.7	*2.52*	29.2	*2.56*	23.8	*3.84*	22.9	*1.34*	26.9	*2.13*
Total-N (kg/t)	8.4	*0.71*	7.7	*0.51*	6.7	*1.26*	6.7	*0.38*	7.4	*0.41*
NH_4-N (kg/t)	0.17	*0.07*	0.37	*0.22*	0.12	*0.05*	0.64	*0.33*	0.32	*0.12*
NO_3-N (kg/t)	0.18	*0.09*	0.14	*0.04*	0.30	*0.24*	0.32	*0.18*	0.23	*0.04*
Total-P (kg/t)	1.41	*0.19*	2.55	*0.58*	1.29	*0.25*	3.86	*0.61*	2.28	*0.60*
Total-K (kg/t)	11.6	*1.22*	7.94	*1.53*	7.69	*2.21*	6.31	*0.99*	8.39	*1.13*
Total-Mg (kg/t)	1.46	*0.25*	1.79	*0.26*	1.12	*0.21*	2.13	*0.43*	1.62	*0.22*
Total-S (kg/t)	1.84	*0.33*	1.39	*0.13*	1.15	*0.33*	1.80	*0.12*	1.54	*0.17*
Total-Na (kg/t)	1.18	*0.17*	1.16	*0.15*	0.90	*0.19*	0.79	*0.07*	1.01	*0.10*
Organic C (% dm)	41.1	*2.95*	27.4	*3.30*	36.6	*1.81*	32.6	*1.02*	34.4	*2.91*
Lignin-C (% dm)[a]	11.1	*3.39*	11.1	*3.41*	10.0	*3.59*	6.6	*2.62*	9.7	*1.06*
Cellulose-C (%dm)[a]	18.4	*5.46*	13.1	*5.07*	17.6	*5.40*	14.4	*5.47*	15.9	*1.28*
DOC (% dm)[a]	1.26	*0.52*	1.04	*0.36*	1.30	*0.49*	1.11	*0.45*	1.18	*0.06*
Aerobic stability (mg CO2/gVS/d)[a]	8.8	*2.61*	9.5	*4.17*	13.7	*2.29*	9.5	*2.76*	10.4	*1.11*
C:N ratio	16.0	*2.13*	10.2	*0.91*	13.3	*1.28*	11.2	*0.60*	12.7	*1.27*
pH	9.0	*0.03*	8.7	*0.18*	8.4	*0.30*	7.3	*0.00*	8.3	*0.35*
Total Zn (g/t)							188	*13.40*		
Total Cu (g/t)							106	*34.35*		
Total Ni (g/t)							1.17	*0.13*		
Total Cd (g/t)							0.10	*0.01*		
Total Pb (g/t)							1.06	*0.11*		
Total Cr (g/t)							1.17	*0.17*		

[a] Mean of 3 annual applications (2004-2006) only.

Table 2. Cattle & pig slurry (average of 5 annual applications, 2004-2008, with standard error in italics). Results expressed on a fresh weight basis unless otherwise stated.

Site	Gleadthorpe		Harper Adams		Bridgets		Terrington (pig)		Mean	
Application rate (t/ha)	163		179		50		116		127	
Dry matter (%)	2.6	*0.82*	2.07	*0.33*	8.1	*2.91*	1.12	*0.18*	3.5	*1.56*
Total-N (kg/t)	1.75	*0.35*	1.39	*0.18*	3.13	*1.09*	2.13	*0.21*	2.1	*0.37*
NH_4-N (kg/t)	0.78	*0.16*	0.53	*0.14*	1.26	*0.44*	1.70	*0.19*	1.07	*0.26*
NO_3-N (kg/t)	0.01	*0.01*	0.00	*0.00*	0.00	*0.00*	0.01	*0.00*	0.01	*0.00*
Total-P (kg/t)	0.25	*0.07*	0.17	*0.05*	0.56	*0.20*	0.16	*0.04*	0.28	*0.09*
Total-K (kg/t)	1.39	*0.11*	0.81	*0.23*	2.27	*0.87*	1.22	*0.10*	1.42	*0.31*
Total-Mg (kg/t)	0.27	*0.04*	0.14	*0.04*	0.37	*0.13*	0.10	*0.03*	0.22	*0.06*
Total-S (kg/t)	0.16	*0.04*	0.14	*0.04*	0.37	*0.13*	0.17	*0.02*	0.21	*0.05*
Total-Na (kg/t)	0.15	*0.03*	0.21	*0.09*	0.46	*0.16*	0.28	*0.04*	0.3	*0.07*
Organic C (% dm)	43.3	*4.37*	32.9	*1.25*	40.1	*1.37*	29.6	*2.04*	36.5	*3.18*
Lignin-C (% dm)[a]	4.87	*1.50*	5.25	*2.95*	5.58	*2.02*	1.95	*0.75*	4.4	*0.84*
Cellulose-C (%dm)[a]	8.0	*2.90*	6.04	*2.70*	12.3	*4.59*	1.47	*0.57*	6.9	*2.25*
DOC (% dm)[a]	5.9	*1.83*	9.08	*3.72*	1.3	*0.47*	5.72	*2.05*	5.5	*1.60*
C:N ratio	6.1	*1.06*	5.0	*0.84*	8.2	*2.32*	1.6	*0.29*	5.2	*1.38*
pH	7.2	*0.11*	7.3	*0.09*	5.5	*1.83*	7.6	*0.08*	6.9	*0.48*
Total Zn (g/t)							10.5	*3.31*		
Total Cu (g/t)							4.06	*1.25*		
Total Ni (g/t)							0.28	*0.06*		
Total Cd (g/t)							0.03	*0.00*		
Total Pb (g/t)							0.50	*0.00*		
Total Cr (g/t)							0.13	*0.03*		

[a] Mean of 3 annual applications (2004-2006) only.

Table 3. Green compost (average of 5 annual applications, 2004-2008, with standard error in italics). Results expressed on a fresh weight basis unless otherwise stated.

Site	Gleadthorpe		Harper Adams		Bridgets		Terrington		Mean	
Application rate (t/ha)	44		45		40		36		41	
Dry matter (%)	54.4	*0.98*	54.4	*0.52*	58.4	*1.82*	61.8	*2.4*	57.3	*1.80*
Total-N (kg/t)	6.13	*0.33*	6.00	*0.12*	6.46	*0.11*	6.86	*0.3*	6.36	*0.19*
NH_4-N (kg/t)	0.02	*0.01*	0.02	*0.01*	0.03	*0.00*	0.03	*0.00*	0.03	*0.00*
NO_3-N (kg/t)	0.08	*0.05*	0.10	*0.02*	0.09	*0.04*	0.09	*0.05*	0.09	*0.01*
Total-P (kg/t)	1.12	*0.06*	1.08	*0.06*	1.10	*0.05*	1.17	*0.03*	1.12	*0.02*
Total-K (kg/t)	3.43	*0.67*	2.85	*0.51*	2.68	*0.42*	4.42	*0.20*	3.34	*0.39*
Total-Mg (kg/t)	1.54	*0.07*	1.58	*0.11*	1.49	*0.12*	1.67	*0.06*	1.57	*0.04*
Total-S (kg/t)	1.01	*0.07*	0.85	*0.04*	0.87	*0.03*	0.99	*0.0*	0.93	*0.04*
Total-Na (kg/t)	0.25	*0.06*	0.18	*0.0*	0.17	*0.04*	0.33	*0.0*	0.23	*0.04*
Organic C (% dm)	14.7	*1.31*	11.9	*0.69*	13.1	*1.02*	10.9	*0.27*	12.7	*0.81*
Lignin-C (% dm)[a]	9.08	*2.85*	11.3	*3.67*	10.3	*3.03*	9.51	*2.8*	10.1	*0.50*
Cellulose-C (%dm)[a]	4.94	*1.70*	4.31	*1.6*	4.55	*1.67*	3.72	*1.1*	4.38	*0.26*
DOC (% dm)[a]	0.11	*0.04*	0.08	*0.0*	0.08	*0.03*	0.10	*0.0*	0.09	*0.01*
Aerobic stability (mg CO2/gVS/d)[a]	2.31	0.9	1.26	*0.3*	2.98	*1.13*	2.01	*0.6*	2.14	*0.36*
C:N ratio	13.1	1.1	10.8	*0.56*	11.9	*0.86*	9.90	*0.35*	11.4	*0.70*
pH	8.14	0.1	7.93	*0.12*	8.01	*0.09*	7.82	*0.12*	7.98	*0.07*

[a] Mean of 3 annual applications (2004-2006) only.

Table 4. Paper crumble (average of 5 annual applications, 2004-2008, with standard error in italics). Results expressed on a fresh weight basis unless otherwise stated.

Site	Gleadthorpe		Harper Adams		Bridgets		Terrington		Mean	
Application rate (t/ha)	74.6		75.6		62.8		65.6		69.7	
Dry matter (%)	40.1	*0.64*	43.0	*3.2*	45.4	*1.1*	46.8	*1.53*	43.8	*1.46*
Total-N (kg/t)	2.18	*0.18*	2.16	*0.18*	1.96	*0.1*	1.97	*0.21*	2.06	*0.06*
NH_4-N (kg/t)	0.03	*0.01*	0.14	*0.11*	0.05	*0.01*	0.03	*0.01*	0.06	*0.03*
NO_3-N (kg/t)	0.01	*0.01*	0.02	*0.01*	0.01	*0.00*	0.01	*0.01*	0.01	*0.00*
Total-P (kg/t)	0.21	*0.01*	0.20	*0.03*	0.17	*0.02*	0.18	*0.01*	0.19	*0.01*
Total-K (kg/t)	0.19	*0.01*	0.18	*0.04*	0.14	*0.02*	0.20	*0.01*	0.18	*0.01*
Total-Mg (kg/t)	0.94	*0.17*	0.77	*0.10*	0.88	*0.1*	0.81	*0.14*	0.85	*0.04*
Total-S (kg/t)	0.82	*0.09*	0.75	*0.11*	0.65	*0.2*	1.11	*0.56*	0.83	*0.10*
Total-Na (kg/t)	0.12	*0.01*	0.10	*0.0*	0.10	*0.02*	0.12	*0.02*	0.11	*0.01*
Organic C (% dm)	20.7	*2.67*	14.7	*1.74*	14.6	*1.2*	14.3	*1.15*	16.1	*1.54*
Lignin-C (% dm)[a]	3.44	*1.00*	3.49	*1.04*	3.67	*1.1*	3.95	*1.21*	3.64	*0.12*
Cellulose-C (%dm)[a]	12.2	*3.78*	12.4	*4.84*	10.2	*4.04*	10.5	*3.69*	11.3	*0.55*
DOC (% dm)[a]	0.84	*0.26*	0.80	*0.27*	0.15	*0.08*	0.41	*0.16*	0.55	*0.17*
Aerobic stability (mg CO2/gVS/d)[a]	17.9	*1.30*	13.1	*1.5*	14.0	*3.00*	15.4	*1.42*	15.1	*1.05*
C:N ratio	39.1	*6.07*	29.7	*3.9*	35.5	*6.09*	36.2	*6.32*	35.1	*1.98*
pH	7.17	*0.13*	7.15	*0.1*	7.61	*0.23*	7.30	*0.00*	7.31	*0.11*

[a] Mean of 3 annual applications (2004-2006) only.

Table 5. Broiler litter (average of 5 annual applications, 2004-2008, with standard error in italics). Results expressed on a fresh weight basis unless otherwise stated.

Site	Gleadthorpe	
Application rate (t/ha)	5-25	
Dry matter (%)	68.2	*2.85*
Total-N (kg/t)	23.0	*2.19*
NH_4-N (kg/t)	4.47	*1.24*
NO_3-N (kg/t)	0.83	*0.39*
Uric acid N (kg/t)	1.87	*1.08*
Total-P (kg/t)	8.73	*0.66*
Total-K (kg/t)	18.6	*1.71*
Total-Mg (kg/t)	2.95	*0.40*
Total-S (kg/t)	3.68	*0.43*
Total-Na (kg/t)	2.42	*0.34*
Organic C (% dm)	37.1	*0.53*
Lignin-C (% dm)[a]	8.17	*2.55*
Cellulose-C (%dm)[a]	21.5	*6.22*
DOC (% dm)[a]	4.18	*2.08*
Aerobic stability (mg CO2/gVS/d)[a]	10.9	*1.24*
C:N ratio	13.2	*1.34*
pH	7.93	*0.32*
Total Zn (g/t)	243	*26.2*
Total Cu (g/t)	60.3	*8.49*
Total Ni (g/t)	3.3	*0.45*
Total Cd (g/t)	0.2	*0.04*
Total Pb (g/t)	1.9	*0.11*
Total Cr (g/t)	3.4	*0.30*

[a] Mean of 3 annual applications (2004-2006) only.

Appendix 4. Soil bio-physical and physico-chemical properties.

Table 1. Soil chemical properties at the crop residue experimental sites. Standard errors in italics

Site	Treatment (N applied kg/ha)	OC (g/kg)		LFOC (g/kg)		DOC (mg/kg)		Tot N (g/kg)		Ext. P (mg/l)		Ext. K (mg/l)		pH		CEC (Meq/100g)	
1. Gleadthorpe																	
	0	9.5	*0.65*	0.72	*0.06*	<0.01		1.10	*0.00*	15	*0.48*	138	*4.48*	6.7	*0.05*	6.2	*1.13*
	50	8.6	*0.78*	1.00	*0.05*	0.9	*0.89*	1.20	*0.04*	13	*0.85*	126	*9.85*	6.4	*0.09*	5.8	*0.85*
	100	10.2	*0.53*	0.86	*0.07*	3.1	*2.56*	1.15	*0.05*	12	*1.03*	120	*13.1*	6.5	*0.07*	3.7	*0.29*
	150	10.6	*0.41*	1.12	*0.12*	3.0	*1.34*	1.20	*0.06*	12	*0.25*	120	*14.8*	6.5	*0.08*	5.5	*1.53*
	200	11.2	*0.81*	1.18	*0.11*	5.6	*2.00*	1.25	*0.12*	14	*0.71*	116	*7.85*	6.2	*0.09*	4.9	*1.40*
	250	10.0	*0.55*	1.14	*0.10*	4.0	*2.22*	1.18	*0.10*	13	*0.65*	106	*7.56*	6.3	*0.03*	5.3	*0.92*
2. Morley																	
	0	9.7	*0.20*	0.18	*0.02*	6.4	*1.67*	1.30	*0.04*	75	*3.94*	123	*2.87*	7.6	*0.04*	10.1	*0.57*
	50	9.1	*0.92*	0.35	*0.06*	10.1	*0.68*	1.30	*0.00*	71	*4.03*	115	*8.51*	7.5	*0.10*	9.7	*0.90*
	100	10.2	*0.49*	0.37	*0.03*	7.7	*0.69*	1.30	*0.04*	69	*2.78*	104	*2.59*	7.5	*0.04*	9.9	*0.50*
	150	10.4	*0.55*	0.33	*0.06*	8.3	*1.22*	1.33	*0.03*	68	*4.15*	102	*3.80*	7.5	*0.05*	8.8	*0.64*
	200	10.2	*0.60*	0.35	*0.04*	6.0	*0.78*	1.45	*0.03*	65	*2.59*	93	*2.29*	7.4	*0.06*	11.1	*0.96*
	250	10.1	*0.57*	0.36	*0.07*	5.3	*1.39*	1.50	*0.04*	65	*4.64*	92	*3.75*	7.2	*0.07*	10.8	*0.44*
3. Ropsley																	
	0	11.6	*0.73*	0.42	*0.04*	13.8	*3.35*	1.28	*0.03*	19	*2.04*	160	*7.84*	6.7	*0.32*	9.4	0.42
	35	13.2	*0.59*	0.46	*0.03*	13.2	*3.08*	1.33	*0.06*	15	*0.65*	147	*6.86*	6.6	*0.12*	9.4	0.36
	70	13.4	*1.27*	0.47	*0.04*	14.4	*1.98*	1.38	*0.03*	15	*2.33*	144	*9.28*	6.6	*0.09*	9.5	0.37
	105	13.0	*1.03*	0.45	*0.01*	15.6	*1.17*	1.50	*0.04*	14	*1.49*	140	*7.97*	6.5	*0.14*	9.2	0.34
	140	12.5	*1.01*	0.53	*0.06*	13.9	*1.50*	1.35	*0.05*	14	*0.95*	129	*8.51*	6.6	*0.17*	10.1	0.44
	175	12.1	*0.87*	0.48	*0.06*	15.7	*2.68*	1.38	*0.05*	12	*1.22*	120	*6.55*	6.4	*0.05*	10.0	0.29
	210	13.7	*1.00*	0.44	*0.01*	18.5	*1.01*	1.45	*0.06*	12	*1.11*	125	*5.25*	6.2	*0.07*	10.0	0.24
	245	14.2	*0.67*	0.55	*0.05*	15.0	*1.48*	1.43	*0.05*	13	*0.65*	128	*7.37*	6.2	*0.28*	10.2	0.39

Table 2 Soil chemical properties at the organic material experimental sites. Standard errors in italics

Site	Treatment	OC (g/kg)		LFOC (g/kg)		DOC (mg/kg)		Tot N (g/kg)		Ext. P (mg/l)		Ext. K (mg/l)		pH		CEC (Meq/100g)	
4. Gleadthorpe																	
	Control	7.1	*0.36*	0.84	*0.06*	17.5	*3.02*	1.07	*0.07*	37	*0.67*	47	*1.20*	6.0	*0.18*	3.0	*0.25*
	5 t/ha BL	8.6	*0.98*	0.96	*0.04*	19.2	*0.08*	1.23	*0.09*	53	*6.11*	101	*15.1*	6.2	*0.03*	3.4	*0.26*
	10 t/ha BL	8.5	*0.46*	1.51	*0.13*	27.9	*3.10*	1.30	*0.00*	68	*3.38*	114	*5.24*	6.2	*0.09*	3.1	*0.19*
	15 t/ha BL	9.1	*1.05*	1.96	*0.32*	30.7	*1.27*	1.33	*0.09*	70	*3.28*	146	*13.0*	6.3	*0.07*	4.1	*0.15*
	20 t/ha BL	8.9	*1.11*	2.06	*0.33*	31.8	*3.20*	1.50	*0.00*	76	*3.18*	178	*8.97*	6.4	*0.17*	3.7	*0.19*
	25 t/ha BL	13.9	*2.15*	3.22	*0.09*	41.3	*0.77*	1.73	*0.07*	109	*7.94*	202	*9.02*	6.3	*0.12*	4.7	*0.13*
	Cattle FYM	7.5	*0.32*	1.35	*0.20*	18.5	*0.54*	1.20	*0.06*	49	*9.29*	163	*13.9*	6.6	*0.12*	3.1	*0.13*
	Cattle slurry	8.8	*0.91*	0.75	*0.02*	16.4	*0.41*	1.23	*0.03*	50	*9.96*	111	*9.24*	6.4	*0.07*	3.4	*0.38*
	Compost	7.5	*0.49*	0.95	*0.25*	16.1	*0.87*	1.23	*0.03*	49	*10.0*	114	*8.82*	6.5	*0.12*	3.6	*0.06*
	Paper	8.0	*0.09*	1.15	*0.22*	17.5	*0.41*	1.30	*0.00*	46	*5.84*	83	*3.38*	6.7	*0.15*	3.5	*0.26*
5. Harper Adams																	
	Control	13.4	*1.57*	0.64	*0.08*	20.8	*1.26*	1.63	*0.03*	76	*6.0*	103	*16.3*	6.9	*0.07*	3.8	*0.48*
	Cattle FYM	16.7	*1.03*	1.31	*0.06*	28.4	*4.54*	2.17	*0.15*	94	*7.8*	447	*18.2*	7.2	*0.13*	4.7	*0.38*
	Cattle slurry	14.3	*1.13*	0.71	*0.06*	29.3	*8.27*	1.80	*0.06*	70	*6.0*	225	*10.6*	7.0	*0.09*	3.7	*0.31*
	Compost	12.9	*0.94*	1.28	*0.03*	29.6	*3.35*	1.87	*0.15*	71	*5.4*	171	*20.9*	7.1	*0.38*	4.1	*0.26*
	Paper	14.4	*0.84*	0.71	*0.13*	11.3	*1.24*	1.73	*0.07*	67	*2.0*	119	*3.5*	7.3	*0.19*	4.3	*0.49*
6. Bridgets																	
	Control	30.4	*1.04*	0.61	*0.03*	9.5	*2.38*	3.57	*0.09*	20	*3.21*	128	*9.40*	8.5	*0.09*	16.8	*0.80*
	Cattle FYM	32.1	*1.86*	1.43	*0.37*	30.5	*5.24*	3.90	*0.25*	41	*6.39*	391	*11.1*	8.6	*0.03*	17.9	*0.74*
	Cattle slurry	30.5	*1.89*	0.85	*0.26*	16.4	*3.87*	3.80	*0.10*	39	*2.91*	397	*34.8*	8.5	*0.03*	18.2	*0.39*
	Compost	29.0	*0.58*	1.19	*0.03*	4.1	*2.09*	3.80	*0.26*	21	*1.86*	211	*14.8*	8.5	*0.00*	16.6	*0.78*
	Paper	28.0	*0.98*	0.99	*0.17*	0.5	*0.46*	3.63	*0.15*	19	*3.53*	147	*21.0*	8.6	*0.03*	16.9	*0.47*
7. Terrington																	
	Control	15.5	*0.55*	0.90	*0.14*	7.05	*4.93*	1.70	*0.06*	30	*2.65*	269	*15.2*	8.3	*0.00*	11.6	*0.29*
	Cattle FYM	15.7	*0.26*	1.79	*0.08*	12.6	*1.16*	1.97	*0.07*	66	*7.09*	444	*34.9*	8.4	*0.06*	11.9	*0.45*
	Cattle slurry	14.4	*0.64*	1.22	*0.07*	4.74	*3.75*	1.67	*0.03*	42	*0.33*	345	*20.7*	8.4	*0.03*	11.3	*0.04*
	Compost	15.2	*0.78*	1.05	*0.09*	12.8	*8.20*	1.93	*0.19*	34	*7.55*	292	*31.1*	8.3	*0.09*	11.6	*1.00*
	Paper	15.5	*0.57*	1.46	*0.11*	1.29	*1.29*	1.70	*0.00*	33	*2.03*	277	*9.91*	8.5	*0.03*	11.1	*0.28*

Table 3. Soil biological properties at the crop residue experimental sites. Standard errors in italics

Site	Treatment (N applied kg/ha)	Microbial biomass (mg/kg)				Fungal biomass (mg/kg)		CO_2-C (mg/kg/hour)		PMN (mg/kg)	
		C		N							
1. Gleadthorpe											
	0	71.6	*19.6*	20.5	*1.55*	0.73	*0.08*	0.42	*0.09*	13.0	*0.71*
	50	83.6	*13.2*	22.7	*2.90*	0.67	*0.14*	0.61	*0.07*	14.5	*1.32*
	100	91.7	*6.7*	23.8	*1.81*	0.83	*0.06*	0.52	*0.11*	17.9	*0.74*
	150	90.0	*15.6*	30.5	*2.27*	0.74	*0.10*	0.53	*0.07*	14.2	*0.67*
	200	91.6	*17.5*	25.9	*1.42*	0.78	*0.12*	0.58	*0.15*	17.6	*2.62*
	250	102.9	*14.8*	24.1	*2.70*	0.97	*0.10*	0.71	*0.15*	15.7	*2.05*
2. Morley											
	0	137.5	*14.9*	31.2	*1.16*	0.26	*0.36*	1.26	*0.24*	22.2	*2.32*
	50	130.7	*19.2*	41.3	*2.53*	0.51	*0.46*	1.42	*0.28*	25.8	*1.12*
	100	101.8	*23.2*	40.0	*5.34*	0.57	*0.56*	1.14	*0.26*	26.3	*2.54*
	150	121.4	*14.7*	42.5	*1.85*	0.67	*0.66*	1.05	*0.07*	32.1	*1.54*
	200	113.4	*7.14*	44.1	*2.96*	0.76	*0.76*	1.24	*0.10*	32.2	*1.68*
	250	128.2	*1.85*	41.6	*3.64*	0.71	*0.86*	1.11	*0.10*	34.8	*4.04*
3. Ropsley											
	0	52.1	*15.6*	25.4	*1.14*	1.09	*0.04*	0.52	*0.05*	27.9	*1.96*
	35	60.4	*10.9*	27.9	*1.77*	1.06	*0.05*	0.44	*0.03*	28.3	*3.02*
	70	38.1	*1.4*	27.9	*2.49*	1.17	*0.11*	0.47	*0.08*	27.6	*0.98*
	105	60.2	*7.9*	32.0	*2.05*	1.28	*0.11*	0.61	*0.08*	28.9	*2.91*
	140	79.4	*15.7*	26.7	*1.74*	1.19	*0.16*	0.65	*0.16*	27.3	*2.05*
	175	52.9	*14.7*	27.8	*2.54*	1.40	*0.06*	0.60	*0.12*	28.3	*1.59*
	210	71.7	*33.1*	25.4	*2.31*	1.31	*0.20*	0.62	*0.11*	28.5	*1.33*
	245	81.0	*5.9*	25.6	*3.06*	1.60	*0.24*	0.51	*0.07*	35.2	*4.07*

Table 4. Soil biological properties at the organic material experimental sites. Standard errors in italics

Site	Treatment	Microbial biomass (mg/kg)				Fungal biomass (mg/kg)		CO_2-C (mg/kg/hour)		PMN (mg/kg)	
		C		N							
4. Gleadthorpe											
	Control	79.4	*8.49*	19.9	*4.74*	0.70	*0.07*	0.50	*0.03*	7.3	*2.32*
	5 t/ha BL	60.8	*6.85*	20.9	*1.59*	0.79	*0.06*	0.45	*0.09*	13.3	*0.58*
	10 t/ha BL	49.0	*29.1*	22.9	*6.41*	1.00	*0.14*	0.66	*0.10*	14.9	*3.08*
	15 t/ha BL	66.3	*7.17*	27.6	*0.94*	1.04	*0.13*	0.82	*0.13*	17.4	*0.19*
	20 t/ha BL	61.7	*34.2*	30.5	*1.76*	0.94	*0.04*	1.03	*0.12*	17.6	*1.20*
	25 t/ha BL	65.4	*15.9*	36.2	*5.99*	1.42	*0.33*	0.74	*0.04*	26.3	*2.99*
	Cattle FYM	35.7	*8.78*	21.7	*0.35*	0.83	*0.15*	0.84	*0.06*	9.9	*0.38*
	Cattle slurry	47.9	*29.2*	17.8	*3.14*	0.71	*0.08*	0.85	*0.06*	10.6	*3.35*
	Compost	80.1	*26.9*	16.0	*1.56*	0.65	*0.09*	0.76	*0.12*	11.4	*1.13*
	Paper	58.0	*14.0*	24.6	*2.15*	0.76	*0.09*	0.86	*0.11*	12.2	*2.57*
5. Harper Adams											
	Control	149	*16.0*	25.3	*1.75*	1.96	*0.11*	0.33	*0.001*	20.1	*3.40*
	Cattle FYM	254	*24.3*	35.0	*4.03*	1.52	*0.22*	0.53	*0.001*	34.1	*3.48*
	Cattle slurry	201	*24.4*	28.1	*1.47*	1.97	*0.11*	0.60	*0.061*	31.6	*4.73*
	Compost	190	*30.5*	25.5	*1.21*	1.78	*0.07*	0.33	*0.001*	26.2	*2.18*
	Paper	256	*26.2*	41.6	*3.67*	2.17	*0.21*	1.00	*0.064*	36.6	*1.38*
6. Bridgets											
	Control	743	*20.2*	179	*7.76*	4.26	*0.95*	1.73	*0.14*	85.8	*2.25*
	Cattle FYM	737	*69.3*	191	*5.08*	4.16	*1.13*	2.32	*0.12*	101.0	*2.96*
	Cattle slurry	920	*23.5*	204	*4.03*	3.81	*0.59*	2.38	*0.16*	111.1	*5.57*
	Compost	674	*25.8*	154	*18.4*	3.48	*0.75*	1.89	*0.15*	88.3	*2.01*
	Paper	660	*13.9*	179	*11.5*	3.71	*0.68*	2.32	*0.19*	80.5	*1.47*
7. Terrington											
	Control	357	*15.3*	52.9	*3.07*	1.93	*0.15*	1.94	*0.67*	32.9	*5.01*
	Cattle FYM	423	*21.4*	60.7	*5.07*	2.27	*0.32*	2.56	*0.66*	36.2	*4.47*
	Cattle slurry	390	*21.9*	62.3	*4.47*	1.65	*0.07*	2.32	*0.81*	38.7	*6.34*
	Compost	351	*29.5*	55.5	*2.48*	1.47	*0.05*	1.76	*0.07*	27.6	*0.11*
	Paper	469	*10.5*	60.2	*3.21*	1.84	*0.07*	2.91	*0.58*	32.7	*5.36*

Table 5. Soil physical properties at the crop residue experimental sites. Standard errors in italics

Site	Treatment (N applied kg/ha)	AWC (%)		Porosity (%)		Bulk density (g/cm^3)		Shear strength (kPa)		Penetration resistance (kPa)		Stability-DR* (%)	
1. Gleadthorpe													
	0	16.7	*1.00*	50.0	*0.52*	1.33	*0.01*	15.8	*0.45*	117	*1.56*	8.9	*1.45*
	50	17.7	*1.09*	50.5	*1.47*	1.31	*0.04*	16.9	*1.01*	118	*1.74*	18.0	*2.60*
	100	16.3	*0.63*	50.9	*0.67*	1.30	*0.02*	16.4	*0.93*	118	*1.41*	20.0	*5.68*
	150	17.5	*0.25*	51.6	*0.60*	1.28	*0.02*	17.5	*0.74*	119	*1.97*	12.1	*0.91*
	200	17.1	*0.78*	50.9	*0.95*	1.30	*0.03*	16.5	*0.30*	116	*1.68*	16.9	*1.50*
	250	16.2	*0.68*	50.9	*1.19*	1.30	*0.03*	18.7	*0.60*	114	*1.99*	13.0	*1.34*
2. Morley													
	0	16.1	0.25	42.8	*0.88*	1.51	*0.02*	17.3	*3.23*	178	*10.4*	5.5	*1.20*
	50	15.7	0.25	44.1	*1.00*	1.48	*0.03*	21.0	*4.74*	188	*8.25*	9.8	*2.52*
	100	16.5	0.38	42.8	*1.13*	1.52	*0.03*	19.8	*3.26*	183	*2.90*	12.6	*1.67*
	150	16.1	0.30	43.5	*1.27*	1.50	*0.03*	15.6	*1.94*	163	*8.80*	11.6	*2.64*
	200	16.7	0.20	43.6	*0.07*	1.50	*0.00*	15.7	*1.09*	168	*6.97*	8.1	*2.34*
	250	16.5	0.42	44.0	*1.07*	1.49	*0.03*	18.3	*1.18*	162	*10.7*	9.2	*2.21*
3. Ropsley													
	0	17.5	*0.30*	46.9	*1.05*	1.41	*0.03*	13.4	*1.26*	158	*5.17*	14.2	*0.33*
	35	17.9	*0.43*	46.6	*0.95*	1.42	*0.03*	13.4	*2.80*	154	*5.78*	15.8	*1.50*
	70	18.2	*0.33*	47.4	*0.71*	1.39	*0.02*	13.6	*1.59*	158	*7.87*	13.0	*0.97*
	105	17.3	*0.39*	49.0	*0.59*	1.35	*0.02*	13.0	*2.39*	143	*9.71*	13.3	*1.28*
	140	18.2	*0.39*	46.3	*0.52*	1.42	*0.01*	13.7	*2.06*	145	*9.11*	11.8	*0.66*
	175	18.2	*0.13*	47.7	*0.83*	1.39	*0.02*	12.9	*0.90*	134	*6.81*	14.9	*1.28*
	210	17.8	*0.09*	47.7	*0.33*	1.39	*0.01*	13.3	*1.45*	135	*4.95*	13.5	*1.42*
	245	19.0	*0.32*	47.3	*0.77*	1.40	*0.02*	13.8	*2.47*	160	*6.76*	14.4	*1.14*

Table 6. Soil physical properties at the organic material experimental sites. Standard errors in italics

Site	Treatment	AWC (%)		Porosity (%)		Bulk density (g/cm^3)		Shear strength (kPa)		Penetration resistance (kPa)		Stability-DR* (%)	
4. Gleadthorpe													
	Control	11.7	*0.13*	53.6	*0.70*	1.23	*0.02*	10.6	*0.52*	235	*31.9*	23.9	*0.63*
	5 t/ha BL	13.0	*0.63*	53.1	*0.77*	1.24	*0.02*	10.5	*0.83*	214	*19.1*	20.4	*3.22*
	10 t/ha BL	11.8	*0.31*	55.3	*0.49*	1.18	*0.01*	9.7	*0.50*	235	*12.8*	21.2	*1.94*
	15 t/ha BL	13.8	*0.83*	56.0	*1.65*	1.17	*0.04*	8.9	*0.92*	211	*13.7*	20.9	*3.33*
	20 t/ha BL	13.6	*0.59*	55.0	*1.59*	1.19	*0.04*	9.6	*0.40*	208	*4.3*	27.6	*4.08*
	25 t/ha BL	13.8	*0.33*	59.8	*0.34*	1.07	*0.01*	10.0	*1.38*	186	*20.9*	21.9	*3.76*
	Cattle FYM	12.6	*0.55*	52.9	*0.74*	1.25	*0.02*	9.2	*0.56*	211	*9.4*	25.3	*5.35*
	Cattle slurry	12.6	*0.66*	52.6	*2.00*	1.26	*0.05*	10.0	*1.27*	227	*29.1*	25.1	*2.80*
	Compost	12.4	*0.55*	53.8	*1.51*	1.23	*0.04*	9.6	*1.02*	233	*21.1*	18.6	*2.94*
	Paper	12.7	*0.93*	53.1	*1.92*	1.24	*0.05*	10.5	*0.90*	212	*6.8*	29.7	*5.17*
5. Harper Adams													
	Control	21.7	*0.40*	50.3	*1.80*	1.32	*0.05*	17.3	*0.74*	157	*4.97*	9.1	*0.47*
	Cattle FYM	23.9	*0.42*	50.9	*1.10*	1.30	*0.03*	19.3	*1.83*	155	*16.5*	7.8	*0.47*
	Cattle slurry	22.3	*0.04*	50.1	*0.95*	1.32	*0.03*	19.7	*1.39*	156	*6.81*	8.7	*0.33*
	Compost	23.1	*0.42*	47.6	*0.46*	1.39	*0.01*	17.8	*2.29*	163	*12.5*	8.9	*0.18*
	Paper	20.8	*0.54*	51.1	*1.24*	1.30	*0.03*	18.5	*0.90*	159	*13.6*	9.1	*0.26*
6. Bridgets													
	Control	27.61	*0.67*	64.1	*1.12*	0.95	*0.03*	53.9	*7.13*	462	*30.4*	3.9	*0.03*
	Cattle FYM	28.09	*1.18*	64.0	*0.30*	0.95	*0.01*	62.7	*8.92*	470	*13.0*	3.9	*0.23*
	Cattle slurry	27.49	*1.29*	62.7	*0.85*	0.99	*0.02*	64.1	*9.25*	455	*25.4*	3.4	*0.11*
	Compost	27.90	*1.52*	65.3	*1.28*	0.92	*0.03*	54.4	*4.86*	406	*22.1*	3.9	*0.21*
	Paper	26.83	*1.82*	64.2	*1.39*	0.95	*0.04*	51.3	*4.30*	471	*9.8*	3.5	*0.05*
7. Terrington													
	Control	23.3	*0.17*	45.6	*0.36*	1.44	*0.01*	39.4	*2.01*	84	*6.57*	20.0	*5.44*
	Cattle FYM	25.0	*0.70*	47.1	*0.43*	1.40	*0.01*	38.7	*1.84*	73	*9.45*	27.8	*4.40*
	Cattle slurry	24.3	*0.26*	45.5	*0.37*	1.45	*0.01*	40.8	*1.02*	112	*11.7*	25.2	*7.54*
	Compost	23.2	*0.39*	45.1	*0.65*	1.46	*0.02*	43.3	*2.51*	80	*8.55*	23.7	*5.44*
	Paper	23.4	*0.57*	45.5	*1.07*	1.44	*0.03*	38.5	*2.13*	82	*7.19*	29.3	*0.57*

Appendix 5. Soil fauna at the organic material experimental sites

Table 1. Topsoil free living nematode populations (g/l) at the organic material experimental sites (not determined at site 7: Terrington); treatment mean with standard errors in italics

Site	Treatment	Bacterial feeders		Omnivores		Predators		Plant feeders		Total	
4. Gleadthorpe (April 2006)											
	Control	958	*265*	138	*33*	47	*10*	3137	*410*	4280	*487*
	5 t/ha BL	3750	*814*	218	*32*	98	*45*	2815	*551*	6882	*1077*
	10 t/ha BL	2025	*418*	127	*20*	95	*3*	4077	*442*	6323	*834*
	15 t/ha BL	3500	*719*	182	*46*	58	*10*	2675	*493*	6415	*686*
	20 t/ha BL	5483	*873*	210	*54*	337	*274*	3698	*194*	9728	*1351*
	25 t/ha BL	3633	*817*	92	*10*	35	*10*	3128	*342*	6888	*1093*
	Cattle FYM	1150	*144*	213	*9*	40	*15*	1355	*325*	2758	*310*
	Cattle slurry	417	*58*	117	*62*	43	*22*	1267	*331*	1843	*307*
	Compost	767	*126*	175	*35*	132	*34*	2185	*939*	3258	*1051*
	Paper crumble	1358	*474*	140	*10*	48	*16*	1937	*908*	3483	*770*
5. Harper Adams (April 2007)											
	Control	5550	*978*	300	*46*	175	*50*	9117	*856*	15142	*897*
	Cattle FYM	7308	*2174*	275	*78*	290	*31*	9287	*563*	17160	*2801*
	Cattle slurry	6067	*545*	255	*41*	192	*22*	9445	*2576*	15958	*2370*
	Compost	4883	*749*	338	*73*	353	*66*	10030	*1307*	15605	*1969*
	Paper crumble	6858	*1120*	387	*112*	242	*26*	6567	*1742*	14053	*2639*
6. Bridgets (April 2007)											
	Control	4267	*709*	198	*14*	18	*3*	1697	*132*	6180	*799*
	Cattle FYM	5217	*1319*	128	*3*	83	*30*	2295	*550*	7723	*1859*
	Cattle slurry	7650	*3879*	190	*81*	38	*8*	1370	*168*	9248	*3916*
	Compost	7358	*621*	240	*51*	37	*6*	2560	*595*	10195	*941*
	Paper crumble	5758	*576*	305	*28*	30	*3*	2087	*649*	8180	*1152*

Table 2. Topsoil free living plant feeding nematodes (g/l) at the organic material experimental sites (not determined at site 7: Terrington); treatment mean with standard errors in italics.

Site	Treatment	Stubby root		Stunt/Spiral		Root lesion		Needle		Total	
4. Gleadthorpe (April 2006)											
	Control	133	*30*	2758	*350*	92	*55*	35	*20*	3018	*430*
	5 t/ha BL	167	*44*	2325	*565*	50	*38*	103	*75*	2645	*495*
	10 t/ha BL	67	*8*	3833	*408*	8	*8*	35	*16*	3943	*412*
	15 t/ha BL	83	*36*	2375	*414*	25	*14*	37	*6*	2520	*464*
	20 t/ha BL	58	*22*	3433	*178*	25	*14*	45	*8*	3562	*175*
	25 t/ha BL	8	*8*	3000	*359*	42	*30*	3	*3*	3053	*348*
	Cattle FYM	108	*36*	1017	*355*	33	*22*	18	*16*	1177	*390*
	Cattle slurry	117	*68*	942	*298*	8	*8*	15	*15*	1082	*349*
	Compost	100	*52*	1817	*828*	50	*38*	42	*21*	2008	*872*
	Paper crumble	108	*60*	1600	*849*	25	*0*	13	*13*	1747	*904*
5. Harper Adams (April 2007)											
	Control	1467	*744*	1675	*376*	508	*133*	67	*27*	3717	*1033*
	Cattle FYM	217	*82*	842	*524*	125	*43*	37	*14*	1220	*461*
	Cattle slurry	792	*384*	1000	*313*	175	*72*	37	*17*	2003	*571*
	Compost	617	*391*	1042	*133*	542	*96*	30	*8*	2230	*471*
	Paper crumble	458	*169*	550	*161*	192	*51*	25	*8*	1225	*365*
6. Bridgets (April 2007)											
	Control	0	*0*	733	*118*	808	*73*	3	*2*	1603	*166*
	Cattle FYM	0	*0*	708	*225*	1400	*449*	2	*2*	2118	*585*
	Cattle slurry	0	*0*	608	*169*	567	*51*	17	*7*	1308	*175*
	Compost	0	*0*	908	*471*	1367	*225*	25	*25*	2383	*659*
	Paper crumble	0	*0*	783	*396*	1117	*297*	27	*27*	1960	*696*

Table 3. Topsoil arthropod populations (number/m^2) at the organic material experimental sites (not determined at site 7: Terrington); treatment mean with standard errors in italics.

Site	Treatment	Mites		Springtails (*Collembola*)		Enchytraeid worms	
4. Gleadthorpe (April 2006)							
	Control	23711	*5048*	8569	*3052*	904	*427*
	5 t/ha BL	16310	*327*	6611	*1143*	1601	*692*
	10 t/ha BL	11601	*2757*	9115	*3398*	1205	*620*
	15 t/ha BL	13070	*6439*	8306	*2517*	998	*317*
	20 t/ha BL	16743	*8449*	12430	*4365*	848	*228*
	25 t/ha BL	11771	*4369*	11244	*3623*	1074	*580*
	Cattle FYM	10415	*1948*	8833	*2335*	339	*149*
	Cattle slurry	16197	*6093*	4972	*1414*	226	*86*
	Compost	14860	*2447*	10283	*3254*	603	*359*
	Paper crumble	11978	*1911*	11206	*1738*	1356	*655*
5. Harper Adams (April 2007)							
	Control	2637	*919*	6479	*1969*	452	*33*
	Cattle FYM	2976	*371*	7929	*873*	603	*185*
	Cattle slurry	3936	*685*	6611	*650*	490	*19*
	Compost	3823	*1068*	5669	*1338*	471	*94*
	Paper crumble	3145	*638*	6837	*1319*	640	*164*
6. Bridgets (April 2007)							
	Control	16347	*1235*	433	*94*	170	*33*
	Cattle FYM	11413	*2284*	546	*132*	283	*118*
	Cattle slurry	12411	*3301*	942	*333*	414	*217*
	Compost	20649	*3705*	652	*320*	192	*17*
	Paper crumble	25595	*4279*	848	*113*	377	*100*

Table 4. Earthworm populations (kg/ha) at the organic material experimental sites (not determined at sit 7: Terrington); treatment means with standard errors in italics.

Site	Treatment	Adults		Juveniles		Total	
4. Gleadthorpe (April 2006)							
	Control	1.6	*0.16*	15.7	*0.52*	17.3	*0.66*
	5 t/ha BL	13.4	*0.75*	12.9	*0.64*	26.3	*1.38*
	10 t/ha BL	2.3	*0.23*	13.8	*0.57*	16.1	*0.54*
	15 t/ha BL	12.7	*0.64*	31.5	*2.06*	44.2	*2.64*
	20 t/ha BL	7.9	*0.47*	41.0	*0.84*	48.9	*1.28*
	25 t/ha BL	12.1	*1.21*	40.0	*0.82*	52.1	*0.89*
	Cattle FYM	33.6	*1.91*	28.1	*0.35*	61.7	*1.67*
	Cattle slurry	7.6	*0.49*	3.4	*0.09*	11.0	*0.44*
	Compost	5.4	*0.54*	8.7	*0.14*	14.1	*0.68*
	Paper crumble	6.9	*0.08*	13.0	*0.15*	19.9	*0.16*
5. Harper Adams (April 2007)							
	Control	119.9	*7.93*	190.0	*8.09*	309.9	*14.51*
	Cattle FYM	483.8	*7.02*	259.1	*6.73*	742.8	*11.60*
	Cattle slurry	311.4	*7.37*	176.2	*4.36*	487.6	*9.37*
	Compost	217.2	*1.78*	105.4	*1.43*	322.6	*2.89*
	Paper crumble	107.1	*4.28*	127.2	*7.19*	234.3	*11.33*
6. Bridgets (April 2007)							
	Control	139.2	*6.5*	34.4	*1.0*	173.6	*6.4*
	Cattle FYM	148.7	*4.5*	70.4	*3.0*	219.1	*2.5*
	Cattle slurry	197.8	*2.1*	99.2	*3.0*	297.0	*1.1*
	Compost	65.9	*3.3*	65.3	*1.6*	131.1	*4.6*
	Paper crumble	114.0	*3.5*	92.1	*4.5*	206.1	*8.0*

Appendix 6. Changes in topsoil organic carbon content.

Table 1. Topsoil organic carbon (g/kg) at the crop residue experimental sites.

Site	Treatment (N applied kg/ha)	Year							
		1992	1994	1998	2000	2001	2005	2006	2008
1. Gleadthorpe									
	0	nd	12.1	nd	10.3	nd	nd	9.5	11.5
	50	nd	nd	nd	12.2	nd	nd	8.6	14.4
	100	nd	12.1	nd	11.3	nd	nd	10.2	11.4
	150	nd	13.3	nd	12.4	nd	nd	10.6	15.0
	200	nd	12.8	nd	13.1	nd	nd	11.2	13.6
	250	nd	nd	nd	11.1	nd	nd	10.0	13.5
2. Morley									
	0	nd	9.9	nd	9.0	nd	9.7	nd	8.4
	50	nd	nd	nd	9.0	nd	9.1	nd	8.5
	100	nd	9.4	nd	9.7	nd	10.2	nd	8.7
	150	nd	9.9	nd	9.6	nd	10.5	nd	8.9
	200	nd	9.9	nd	10.4	nd	10.2	nd	9.1
	250	nd	nd	nd	9.4	nd	10.1	nd	9.0
3. Ropsley									
	0	12.4	nd	12.2	12.2	12.3	nd	11.6	11.4
	35	12.5	nd	12.0	12.3	12.8	nd	13.2	11.6
	70	12.4	nd	13.8	12.5	12.4	nd	13.4	12.8
	105	12.5	nd	13.7	13.1	13.3	nd	13.0	11.8
	140	12.7	nd	13.2	12.7	12.1	nd	12.5	12.4
	175	12.8	nd	12.8	13.4	13.7	nd	12.1	13.1
	210	12.8	nd	13.4	12.8	13.5	nd	13.7	14.5
	245	12.9	nd	13.8	13.1	13.7	nd	14.2	14.5

nd: not determined

Table 2. Topsoil organic carbon at the organic material experimental sites. Standard errors in italics

Site	Treatment	Year					
		1996	1998	2001	2006	2007	2008
4. Gleadthorpe							
	Control	10.7	11.0	13.9	7.1	nd	9.5
	5 t/ha BL	11.6	10.8	11.3	8.6	nd	11.4
	10 t/ha BL	12.0	10.7	15.0	8.5	nd	11.2
	15 t/ha BL	12.3	12.9	13.5	9.1	nd	12.8
	20 t/ha BL	14.4	13.0	14.5	8.9	nd	13.5
	25 t/ha BL	15.5	13.1	18.2	13.9	nd	17.2
	Cattle FYM				7.5	nd	12.5
	Cattle slurry				8.8	nd	12.5
	Compost				8.0	nd	11.1
	Paper				7.5	nd	12.7
5. Harper Adams							
	Control	nd	14.8	15.6	nd	13.4	12.3
	Cattle FYM	nd	15.3	16.6	nd	16.7	15.0
	Cattle slurry	nd	15.3	13.8	nd	14.3	13.4
	Compost				nd	12.9	12.8
	Paper				nd	14.4	13.2
6. Bridgets							
	Control	nd	33.0	29.8	nd	30.4	27.2
	Cattle FYM	nd	30.7	32.5	nd	32.1	33.0
	Cattle slurry	nd	30.6	31.2	nd	30.5	28.7
	Compost				nd	29.0	29.0
	Paper				nd	28.0	28.8
7. Terrington							
	Control	nd	13.9	15.8	nd	15.5	13.5
	Cattle FYM	nd	14.5	18.8	nd	15.7	20.8
	Cattle slurry	nd	15.5	16.6	nd	14.4	15.8
	Compost				nd	15.2	14.6
	Paper				nd	15.5	14.4

The quality of soil organic matter was evaluated on the basis of the soil samples (0-30 cm) collected after seventh rotation in the both cycles 1 and 2(Table 3). The average values for the cycles of described parameters were considered. SOM was expressed as the percentage content of organic carbon in soil.Â The average values for treatments with different rates of manure and mineral N fertilizers describe the effect of experimental factors on soil organic carbon quantity.