Work Package 1 Final report (2010-2015)

DC-Agri; field experiments for quality digestate and compost in agriculture

Work Package 1 report: Effect of repeated digestate and compost applications on soil and crop quality

Project code: OMK001-001/WR1212
Research date: 2010-2015 **Published:** February 2016

WRAP's vision is a world in which resources are used sustainably.

Our mission is to accelerate the move to a sustainable resource-efficient economy through re-inventing how we design, produce and sell products; re-thinking how we use and consume products; and re-defining what is possible through re-use and recycling.

Find out more at www.wrap.org.uk

Document reference (please use this reference when citing WRAP's work): WRAP, 2015, *DC-Agri*; field Experiments for Quality Digestate and Compost in Agriculture – WP1 report, Prepared by Bhogal et al.

Written by: Anne Bhogal, Matthew Taylor, Fiona Nicholson, Alison Rollett, John Williams, Paul Newell Price, Brian Chambers (ADAS), Audrey Litterick (Earthcare Technical), Mark Whittingham (Newcastle University)

Front cover photography: Images courtesy of ADAS

Executive summary

The aim of this work package was to investigate the effects of *repeat applications* (*i.e.* annual applications over a minimum of three years) of compost (green and green/food) and digestate (food- and manure-based) in comparison with farmyard manure (FYM) and livestock slurry on soil and crop quality at a range of experimental sites with varying soil types, climatic conditions and cropping. Accordingly, a network of seven experimental sites was established in autumn 2010 across the UK: Aberdeen (Aberdeenshire), Ayr (Ayrshire), Devizes (Wiltshire), Faringdon (Oxfordshire), Harper Adams (Shropshire), Lampeter (Ceredigion) and Terrington (Norfolk). The sites at Harper Adams and Terrington were existing experimental platforms which had previously benefitted from applications of FYM, livestock slurry and green compost over a 6-17 year period and allowed the effects of longer-term manure applications on soil physiochemical properties to be quantified.

Over the three year experimental programme green compost and FYM applications each supplied *c.*16 t/ha organic matter (OM), green/food compost *c.*11 t/ha OM, livestock slurry *c.*8 t/ha and food-based digestate *c.*2 t/ha OM. Manure-based digestate was applied at Aberdeen and Ayr in Scotland, supplying 3-6 t/ha OM. At the two sites with a prior history of organic material applications, OM loadings of green compost (historical + this work) amounted to *c.* 48 t/ha, with FYM OM loadings of *c.*105 t/ha (Harper Adams – cattle FYM) and *c.*81 t/ha (Terrington – pig FYM). Crop yields were determined every year, with a comprehensive programme of soil and crop quality assessments undertaken in 2013.

The results clearly demonstrated that repeated applications of compost are a valuable means by which farmers can improve soil quality, potentially leading to increases in crop yields (through improved nutrient and water acquisition) and improved gross margins (from greater yields as well as less reliance on manufactured fertiliser and reduced energy costs through easier cultivation). This conclusion was based largely on changes in soil properties achieved after the long-term (9 years) application of green compost at the two sites with a prior history of organic material additions, although the direction of change in soil properties following 3 years of green and green/food compost was the same. The long-term compost applications led to increases in soil organic matter (SOM) which were associated with increases in microbial biomass, earthworm numbers and nutrient supply (both overall topsoil nutrient – nitrogen, phosphorus, potassium, magnesium and sulphur status, as well as cation exchange capacity and potentially mineralisable N), and decreases in soil bulk density. Moreover, repeated compost additions led to a more rapid build-up of SOM compared to FYM due to a higher lignin content, rendering it more resistant to decomposition, confirming its value as a good source of stable OM.

Repeated digestate applications (both food and manure-based) had a limited capacity to improve soil biological and physical functioning, due to the low organic matter loading associated with these materials; nevertheless, the digestates did improve soil nutrient status. However, both digestate and livestock slurry applications increased soil compaction at these sites (as measured by bulk density, shear strength and penetration resistance), although reasons for this are unclear. At the two grassland sites, overall earthworm numbers on the food-based digestate treatments were lower than on all the other treatments, including the fertiliser control. Laboratory studies concluded that ammonium-N loading (a function of both the NH_4-N concentration and application rate) most strongly explained the negative effects observed. However, due to the worst-case nature of these studies (and particularly contact tests) and the fact they do not accurately simulate conditions in the field, it was not possible to recommend a maximum ammonium-N loading.

Both composts and digestates provided an additional source of P, K and S (a 'nutrient boost') to crops leading to higher yields and crop nutrient contents, particularly in 2012 and 2013 (following 2-3 years of repeated additions). This additional nutrient supply was valued at

£55-£160/ha, taking into account the value of fertiliser saved and cost of spreading (but not sourcing) the organic materials, and clearly demonstrated the value of an *integrated nutrient management plan*, using both compost/digestate and manufactured fertiliser.

There was no effect of compost or digestate additions on soil total metal and organic compound contaminant concentrations or crop metal concentrations. This is an important finding and supports the sustainable use of these materials on crops grown for food production.

Contents

Acknowledgements

The authors would like to thank the large number of people at ADAS, Harper Adams University and SRUC who have made an invaluable contribution to this project. In particular, we would like to acknowledge the assistance of Roy Cross, Gail Bennett, Ryan Hickinbotham, Tony Lathwood, Chris Dyer and Helen Kingston (ADAS), Paul Lewis and Grace Smith (Harper Adams University), Oliver Knox, Bill Crookes, Billy Harrison and Robin Walker (SRUC).

The inspiration, enthusiasm, intellectual contribution and leadership of Professor Brian J. Chambers is also recognised; very sadly, Brian passed away before the project had been completed.

1.0 Introduction

1.1 Organic materials

In the United Kingdom, millions of tonnes of biodegradable organic materials are sent to landfill every year. Removing biodegradable waste from landfill will significantly reduce greenhouse gas (GHG) emissions (in particular methane, which has a global warming potential around 20-fold greater than carbon dioxide) and thereby contribute to government targets to reduce GHG emissions. To this end, the EU Landfill Directive states that by 2020 the amount of biodegradable municipal waste disposed of in landfill sites must be reduced by 65%, compared with 1995 levels (EC, 1999). By avoiding sending organic materials to landfill, they are available to be beneficially recycled to land, which has the potential to provide benefits in terms of the sustainable use of plant nutrients and the addition of organic matter to improve soil structural conditions. Composting source-segregated biodegradable wastes to produce green (garden/landscaping waste) and green/food (garden/landscaping and kitchen/food wastes) composts for recycling to agricultural land is increasingly being practiced to divert organic materials away from landfill. Additionally, treating organic materials via anaerobic digestion (AD) can help the UK meet important environmental goals, particularly the generation of renewable energy and reduction of GHG emissions. Therefore, as part of the UK's commitment to meet EU renewable energy targets by 2020, UK governments have put in place policies and strategies to increase the generation of renewable energy and treatment of food waste through AD.

In addition to the generation of renewable energy ('biogas') the AD process produces a nutrient source i.e. digestate (or 'biofertiliser'). The production of both compost and digestate is regulated through the Quality Protocols (for compost and digestate) in England, Wales and Northern Ireland and the PAS Assurance Scheme (PAS 100 for composts and PAS 110 for digestates); in Scotland there is a position statement which producers/users must comply with. These cover all treatment processes from raw materials and production methods through to quality control and lab testing to ensure certified materials are quality assured, traceable, safe and reliable to use. Compost and digestate produced in compliance with these standards at sites certified by the Compost Certification Scheme-CCS or Biofertiliser Certification Scheme-BCS, are considered to be products and are therefore not subject to Environmental Permitting/Waste Management Licensing Regulations when recycled to agricultural land (and other approved end-uses). In addition to the regulatory and good practice requirements, which farmers have to comply with when using compost and digestate, over 90% of farms are covered by farm/crop assurance schemes. These schemes clearly have an interest in ensuring that using compost and digestate will provide a benefit and not cause harm to crops, soil or human/animal health.

1.2 Soil quality

The sustainability of UK agricultural production is dependent on the long-term maintenance of soil function and fertility, which are key aspects of soil quality. Indeed, the importance of maintaining and improving soil quality was highlighted in the Government's Food 2030 strategy (Defra, 2010a). Moreover, Defra's headline indicator for agricultural soil quality is to "maintain and enhance soil organic matter levels". Soil organic matter levels are intimately linked to the soil properties that are important in the maintenance of soil quality and fertility, and sustainable crop production. Of the compost and food-based digestate currently produced in the UK, 68% and 96%, respectively is recycled to agricultural land (WRAP, 2013; 2014). Whilst composts and digestates are recognised as valuable sources of organic matter and plant available nutrients, there is uncertainty about the nutrient supply characteristics of these materials and, because the feedstocks for these materials include garden and food wastes, it is necessary to evaluate whether they might be a source of contamination (in particular heavy metals or organic compound contaminants). In addition to investigating the beneficial aspects of applying organic materials to land, it is essential that the land application (agricultural or otherwise) is not harmful to the environment (i.e. soil, water and air quality) or human health. To provide advice on the sustainable use of these materials, it is therefore important to demonstrate their longer term effects on soil and crop quality, particularly because they are often applied on more than one occasion within a typical agricultural rotation. To this end, the field experiments described here build upon quantitative and semi-quantitative risk assessments that have been undertaken by providing scientifically robust field experimental data on the medium term use of compost and digestate in agriculture.

1.3 Overall programme objectives

The overall objective of the *DC-Agri* experimental programme was to:

- Quantify the effects of contrasting digestate and compost applications on soil and crop quality, crop available nitrogen supply and emissions to the air and water environments.

The project had two separate work packages (WP) to achieve this aim, plus a third WP delivering a comprehensive knowledge exchange programme on the use of digestate and compost in agriculture.

WP1: Quantification of the effects of repeated compost and digestate applications on soil and crop quality.

WP2: Quantification of the nitrogen supply characteristics of contrasting digestate and compost products (WP2.1), including the impact of digestate and compost additions on nitrous oxide and ammonia emissions to air and leaching losses (nitrate, phosphorus and microbial pathogens) to water (WP2.2).

This report covers WP 1.

1.4 WP1 objectives

The aim of this work package was to investigate the effects of *repeat applications* (*i.e.* annual applications over a minimum of three years) of compost (green and green/food) and digestate (food-based) in comparison with farmyard manure (FYM) and livestock slurry on soil physical, chemical and biological properties and crop quality at a range of experimental sites with varying soil types, climatic conditions and cropping throughout the UK.

The specific objectives were to investigate:

- The influence of repeated applications of organic materials on crop yields, quality and safety in each year following application and in subsequent growing seasons;
- The influence of repeated applications of organic amendments on soil organic matter and carbon;
- The influence of repeated applications of organic amendments on soil quality, particularly on concentrations of copper (Cu), zinc (Zn), lead (Pb), mercury (Hg), cadmium (Cd), nickel (Ni), chromium (Cr), arsenic (As), molybdenum (Mo), Selenium (Se) and Fluoride (F);
- The influence of repeated applications of organic amendments on soil microbial biomass carbon/nitrogen, respiration rate and earthworm populations;
- The influence of repeated applications of organic amendments on the concentrations of organic compound contaminants (OCCs) in the soil i.e. polycyclic aromatic hydrocarbons (PAHs), Polychlorinated dibenzo-p-dioxins (PCDDs) and Polychlorinated dibenzofurans (PCDFs) (Dioxins and Furans), polychlorinated biphenyls (PCBs) and phthalates.

2.0 Methodology

2.1 Experimental sites

In autumn 2010, a network of seven sites was established on a range of soil types and across agroclimatic zones: Aberdeen, Ayr, Devizes, Faringdon, Harper Adams, Lampeter and Terrington (Table 1 & Figure 1). The sites at Harper Adams and Terrington were existing experimental platforms and had previously benefitted from applications of FYM, livestock slurry and green compost over a 6-17 year period (depending on the site and treatment) as part of the SOIL-*QC* experimental programme (Defra, 2011), with Harper Adams previously receiving food-based digestate applications for three years (Table 2). Green compost was also applied to the site at Aberdeen for one year prior to experimentation (Table 2).

Table 1. Characteristics and cropping at the soil and crop quality experimental platforms

Site		**Soil textural group**		**Annual rainfall (mm)**	**Cropping rotation**[+]		
		Cross-compliance soil group[1]	**% clay**		**2010-11**	**2011-12**	**2012-13**
1	Aberdeen (Aberdeenshire)	Sandy/light	16	790	SB	WB	WOSR
2	Ayr (Ayrshire)	Medium	19	1,190	G	G	G
3	Devizes (Wiltshire)	Chalk	20	850	Lin	WW	WW
4	Faringdon (Oxfordshire)	Heavy	62	830	WW	WW	WC
5	Harper Adams (Shropshire)	Sandy/light	11	690	POT	SB	WW
6	Lampeter (Ceredigion)	Medium	26	980	G	G	G
7	Terrington (Norfolk)	Medium (heavy)	28	630	WW	WW	WOSR

[+] SB = spring barley; WB = winter barley; WOSR = winter oilseed rape; WW = winter wheat; G = grassland; POT = potatoes; Lin = Linseed; WC = whole crop oats/peas.

[1] EA (2008)

Table 2. Treatment history at the existing experimental platforms prior to the DC-*Agri* experimental programme

Site	**Historic treatment**	**Date first applied**	**Number of applications up to DC-*Agri* (2010)**	**Project code/Reference**
Aberdeen	Green compost (17 t/ha fw)[1] Green compost (34 t/ha fw)[2]	2009	1	Wrap OAV023-017 Litterick *et al.*, (2009)
Harper Adams[3]	Cattle FYM	1990	16	Defra SP0530 (2011) Bhogal *et al.*, (2009)
	Cattle slurry	1990	16	
	Green compost	2005	6	
	Food-based digestate	2006	3	Murray pers.comm.
Terrington[3]	Pig FYM	1993	17	Defra SP0530 (2011) Bhogal *et al.*, (2009)
	Pig slurry	1993	17	
	Green compost	2005	6	

[1] The DC-*Agri* green compost treatment was super-imposed on this treatment

[2] The DC-*Agri* green/food compost treatment was super-imposed on this treatment

[3] Treatments were applied at rates equivalent to *c.*250 kg total N/ha, and continued on the same plots for DC-*Agri*. The 'new' green/food compost (both sites) and food-based digestate (Terrington) treatments were established on new plots that were embedded within the existing experimental design at these sites.

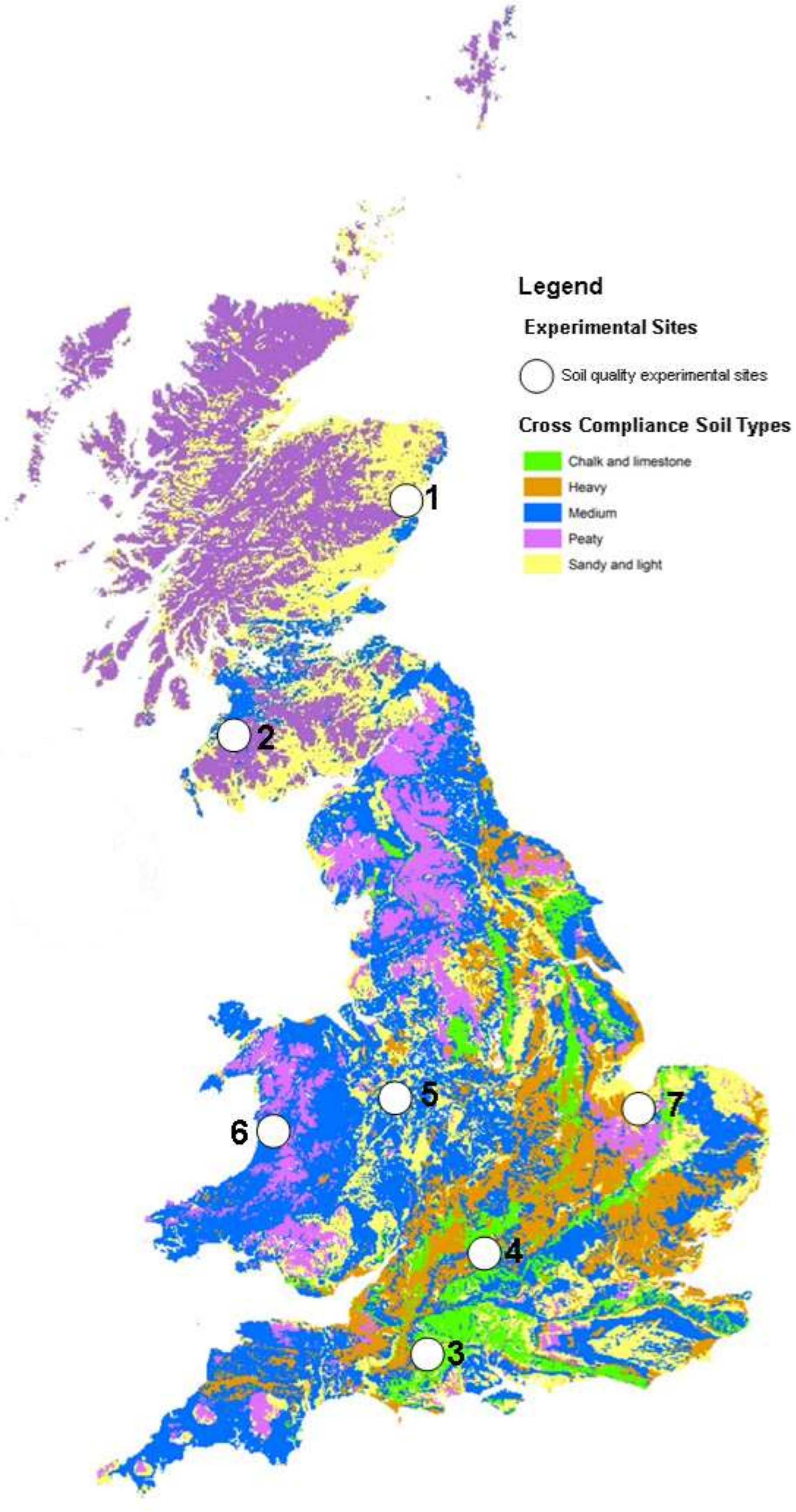


Figure 1 Location of the soil quality experimental platforms

To characterise each site, representative topsoil samples (0-15cm at tillage sites and 0-7.5cm at grassland sites) were taken in either autumn 2010 (Ayr and Terrington) or spring 2011 (Aberdeen, Devizes, Faringdon, Harper Adams, and Lampeter). The soil samples were taken by following established sampling protocols (i.e. following the pattern of a letter 'W' and taking 25 sub-samples at regular intervals from each of the three replicate experimental blocks; Defra, 2010b). The sub-samples were then bulked to form one representative sample per block and submitted for laboratory analysis of pH, sand (%), clay (%), silt (%), extractable phosphorus (P), extractable potassium (K) and extractable magnesium (Mg), extractable sulphate - sulphur (SO_4-S), total nitrogen (N) and organic carbon (C); Table 3. Samples from the Scottish sites were analysed for extractable P, K and Mg using both the standard technique and classification used in England and Wales (Defra, 2010b) and that used in Scotland (SAC, 2010).

Note: For extractable K and Mg the ADAS and SAC methods are identical, but P is extracted using the Olsen method in England and Wales (MAFF, 1986) and the modified Morgan's method in Scotland (SAC, 2010). Although the latter method extracts less P, the interpretation in terms of crop P supply (i.e. the ADAS index and SAC status) is similar for both methods.

Table 3 Baseline topsoil characteristics (site averages; n=3)

Determinand[*]	**Aberdeen**	**Ayr**	**Devizes**	**Faringdon**	**Harper Adams**	**Lampeter**	**Terrington**
pH	5.8	5.2	8.0	7.1	5.7	5.3	8.0
Sand (%)	58	52	16	10	76	33	10
Silt (%)	26	29	64	28	13	41	62
Clay (%)	16	19	20	62	11	26	28
Texture Classification	Sandy loam	Sandy clay loam	Silty clay loam	Clay	Sandy loam	Clay loam	Silty clay loam
Extractable P: mg/l (ADAS Index)[b] mg/l (SAC status)[c]	55 (4) 7.6 (M-)	42 (3) 6.8 (M-)	18 (2)	32 (3)	71 (5)	24 (2)	26 (3)
Extractable K: mg/l (ADAS Index)[b] mg/l (SAC status)[c]	116 (1) 135 (M-)	132 (2-) 119 (M-)	273 (3)	268 (3)	86 (1)	86 (1)	283 (3)
Extractable Mg: mg/l (ADAS Index)[b] mg/l (SAC status)[c]	83 (2) 81 (M-)	174 (3) 166 (M-)	50 (1)	262 (5)	58 (2)	55 (2)	166 (3)
Ext. SO_4-S (mg/l)	10	49	8	15	6	11	29
Total N (% dm)	0.35	0.22	0.70	0.35	0.18	0.49	0.14
Organic C (% dm)	4.80	2.33	4.87	3.37	2.30	4.50	1.62
Organic Matter[a] (% dm)	8.28	4.02	8.39	5.80	3.37	7.76	2.79

[*] mg/l = milligrams/litre; dm = dry matter

[a] Organic carbon multiplied by 1.724 (MAFF, 1986)

[b] ADAS Indices (Defra, 2010b) refer to the relative amounts of soil nutrients which are available to plants and range from 0 (deficient) to 9 (very large).

[c] SAC Status values refer to the relative amounts of soil nutrients which are available to plants and range from very low (VL), low (L), moderate (M), high (H) to very high (VH).

2.2 Treatments and design

At each site, 18 or 21 experimental plots were laid out in a randomised block design (6 or 7 treatments, with 3 replicates of each). The experimental treatments are detailed in Table 4.

Two contrasting compost types were investigated as there are known differences in nutrient and organic matter contents between green and green/food compost (Defra, 2010b). At the two Scottish sites, a manure-based digestate was included as a treatment in addition to the food-based digestate. In the first cropping year, organic material treatments were applied in autumn 2010 at Ayr and Terrington, and at the other sites (Aberdeen, Devizes, Faringdon, Harper Adams and Lampeter) once ground conditions and Nitrate Vulnerable Zone (NVZ) regulations allowed in spring 2011. Organic material applications were repeated in autumn 2011 at Aberdeen, Devizes, Faringdon, Lampeter and Terrington and in spring 2012 at Ayr and Harper Adams, with a final application in autumn 2012 at all seven sites. Cattle farmyard manure (FYM) and slurries were used at all sites (from sources 'local' to each site), except Terrington where pig manures (FYM and slurry) were used (in line with the previous SOIL-*QC* experimental programme). In 2010 the green compost, green/food compost and digestates were obtained from sources in England and for subsequent applications these materials were obtained from one source within each country (i.e. England, Scotland and Wales).

Table 4 Organic material treatment details

Treatment No	Treatment details
1	Control (no organic material application; recommended rates of inorganic fertiliser only)
2	Green compost at 250 kg N/ha (from CCS certified sites; 0-40mm grade)
3	Green/food compost at 250 kg N/ha (from CCS certified sites; 0-40mm grade)
4	Food-based digestate at 120-250 kg N/ha (from BCS certified sites or those producing digestate meeting PAS110 minimum criteria)
5	Farmyard manure at 250 kg N/ha
6	Livestock slurry at 120-250 kg N/ha
7	Manure-based digestate at 120-250 kg N/ha (Aberdeen and Ayr sites only)

2.3 Organic materials

Triplicate samples of each organic material type were taken at the time of spreading every year (*c.*2 litres for each liquid organic material sample and *c.*2 kg for each solid organic material sample). The analysis for each organic material type (averaged across the three years of applications and across all suppliers) is summarised in Table 5.

In some years there were slight discrepancies between the total N analysis provided by the organic material supplier (which was used to calculate application rates) and that determined at the time of application, which, on some occasions, led to N loadings in excess of the target rate (Table 4). *Note:* at all times, all activities complied with the relevant regulations, including the NVZ field limit of 250 kg/ha total N. Over all the sites, the average annual N loading was close to the target ranges, with annual loading rates of *c.*160-250 kg/ha/yr total N, 30-160 kg/ha/yr phosphate (P_2O_5), 92-295 kg/ha/yr potash (K_2O) and 40-190 kg/ha/yr sulphur (S), depending on the treatment (Table 6). FYM supplied the most phosphate, potash and sulphur, compost the most total N (although over 95% of this was in organic forms), and the food-based digestate and livestock slurry supplied the most readily available N (Table 6).

Table 5 Mean organic material analyses, 2010-2013 (standard error in parenthesis)

Determinand	**Units[1]**	**Food-based Digestate (n=21)[2]**	**Manure-based digestate (n=6)**	**Livestock slurry (n=21)**	**Green compost (n=21)**	**Green/food compost (n=21)**	**Farmyard manure (n=21)**
pH	-	8.50 (0.06)	7.64 (0.20)	7.37 (0.09)	8.26 (0.09)	7.91 (0.10)	8.16 (0.13)
Dry Matter	%	2.16 (0.18)	2.75 (0.67)	4.60 (0.47)	70 (3.0)	66 (1.66)	27 (2.25)
Total Nitrogen (N)	kg/t fw	4.67 (0.18)	2.08 (0.30)	2.67 (0.14)	9.59 (0.49)	11.8 (0.63)	6.67 (0.53)
Readily Available N (RAN)[3]	kg/t fw	3.78 (0.17)	1.13 (0.10)	1.44 (0.12)	0.24 (0.03)	0.81 (0.10)	0.46 (0.09)
% of total Nitrogen		*81* *(1.54)*	*58* *(4.79)*	*54* *(3.2)*	*2* *(0.34)*	*7* *(0.54)*	*7* *(1.36)*
Total Phosphate (P_2O_5)	kg/t fw	0.61 (0.07)	0.61 (0.20)	0.69 (0.05)	3.59 (0.21)	4.16 (0.30)	4.27 (0.54)
Total Potash (K_2O)	kg/t fw	1.96 (0.08)	2.11 (0.31)	2.29 (0.17)	6.93 (0.48)	6.48 (0.28)	7.98 (0.90)
Extractable Potash (K_2O)	kg/t fw	1.70 (0.13)	1.89 (0.25)	1.94 (0.18)	5.20 (0.36)	5.06 (0.32)	6.24 (0.70)
% of total K_2O		*89* *(6.45)*	*99* *(17.2)*	*87* *(6.24)*	*76* *(3.12)*	*77* *(3.04)*	*80* *(3.71)*
Total Magnesium (MgO)	kg/t fw	0.07 (0.01)	0.39 (0.11)	0.49 (0.05)	3.68 (0.16)	3.66 (0.15)	2.65 (0.22)
Total Sulphur (SO_3)	kg/t fw	0.36 (0.06)	0.53 (0.14)	0.78 (0.16)	3.30 (0.19)	3.74 (0.14)	5.23 (0.93)
Total Calcium	kg/t fw	0.69 (0.11)	0.46 (0.12)	1.42 (0.36)	16.3 (1.51)	18.7 (1.24)	8.76 (1.43)
Organic Carbon	% dm	33.7 (0.88)	36.8 (2.70)	38.0 (1.02)	17.2 (0.72)	18.4 (0.63)	30.5 (1.75)
Lignin Carbon	% dm	6.74 (1.02)	8.61 (1.34)	6.81 (0.75)	11.5 (0.59)	10.9 (0.40)	17.0 (1.51)
% of total Carbon		*21* *(2.91)*	*24* *(4.12)*	*18* *(1.89)*	*68* *(2.98)*	*62* *(2.95)*	*55* *(3.79)*
Organic Matter[4]	% dm	58.2 (1.52)	63.5 (4.66)	65.5 (1.76)	29.7 (1.24)	31.8 (1.09)	52.6 (3.02)
Loss on Ignition	% dm	54.0 (1.83)	64.3 (6.63)	71.1 (2.35)	34.7 (1.53)	35.5 (1.12)	62.3 (3.42)
Total Neutralising Value	% CaO dm	n.d	n.d	20.3 (5.33)	3.33 (0.29)	3.90 (0.29)	4.62 (0.45)
Total Zinc	mg/kg dm	136 (8.32)	168 (20.5)	257 (41.2)	234 (13.5)	278 (21.0)	280 (49.5)
Total Copper	mg/kg dm	45.5 (5.04)	184 (28.9)	152 (36.0)	66.1 (5.8)	74.1 (6.36)	65.3 (9.55)
Total Cadmium	mg/kg dm	<0.50	<0.50	0.34 (0.05)	0.62 (0.06)	1.07 (0.14)	0.29 (0.03)
Total Nickel	mg/kg dm	42.5 (9.05)	9.40 (1.70)	8.07 (1.59)	17.9 (0.89)	18.6 (2.95)	7.25 (0.92)
Total Lead	mg/kg dm	7.14 (0.96)	8.22 (1.02)	9.13 (2.79)	120 (11.3)	91.8 (4.91)	10.7 (2.27)
Total Chromium	mg/kg dm	7.82 (0.68)	12.6 (6.7)	3.89 (0.57)	22.3 (1.52)	21.8 (1.08)	6.86 (0.98)
Total Mercury	mg/kg dm	<2.30	<2.40	1.45 (0.45)	0.20 (0.02)	0.15 (0.01)	<0.05
Total Molybdenum	mg/kg dm	9.7 (1.47)	3.55 (0.84)	4.94 (0.79)	2.28 (0.17)	2.78 (0.17)	4.49 (0.75)
Total Fluoride	mg/kg dm	<370	<890	<340	16.3 (1.91)	18.7 (2.25)	11.9 (1.34)
Total Selenium	mg/kg dm	8.6 (3.1)	2.03 (1.43)	1.19 (0.17)	0.42 (0.02)	0.40 (0.02)	0.73 (0.13)
Total Arsenic	mg/kg dm	1.11 (0.13)	1.05 (0.14)	1.21 (0.21)	8.12 (0.62)	8.26 (0.54)	2.24 (0.37)

[1] kg/t fw = kilograms/tonne fresh weight; %dm = percent dry matter; %CaO dm = percent calcium oxide on a dry matter basis; mg/kg dm = milligrams/kilogram dry matter; n.d: not determined; [2]n=number of sites and seasons (mean of samples taken from seven sites in each of 3 seasons for most organic materials); three replicate samples were taken at each site in each season. The farm manures were sourced locally to each site, the compost and digestate was sourced from a single supplier in each country (i.e. 3 different suppliers – England, Wales & Scotland); [3]Readily available nitrogen (RAN = ammonium-N & nitrate-N); [4]Organic carbon multiplied by 1.724 (MAFF, 1986)

Table 6 Average annual nutrient loadings across the 7 experimental sites and three growing seasons (n=21)

Treatment	**Average annual loading rate (kg/ha/yr)**				
	Total N	**RAN**[2]	**P_2O_5**	**K_2O**	**S**
Green compost	261	6	97	186	89
Green/food compost	211	14	74	117	67
Food-based digestate	220	178	29	92	16
FYM	247	17	159	294	193
Livestock slurry	192	102	51	167	58
Manure-based digestate[1]	161	88	43	157	38

[1] Aberdeen & Ayr only (n= 6); [2] RAN = Readily Available Nitrogen (ammonium-N and nitrate-N)

2.4 Crop management

The crop rotations for each site are detailed in Table 1. Crops were grown according to best farm practice, using commercially recommended seed rates, with crop protection products applied according to advice from a BASIS qualified adviser and according to good agricultural practice to control weeds, pests and diseases, with the aim of growing healthy and productive crops.

Applications of manufactured fertiliser (N, phosphate, potash and S) were made where necessary, based on crop requirements, after accounting for the N supplied by the organic materials (Defra, 2010b; SAC, 2010), to ensure (as far as is practically possible) that no major nutrient limited crop growth, and that crop yields and residue returns were the same on all treatments (i.e. the only difference in organic carbon inputs was from the applied organic material treatments). All recommendations were based on MANNER-*NPK* (Nicholson *et al.,* 2013) predictions of organic material crop available N supply, using the latest nutrient analyses provided by the suppliers, and checked by a Fertiliser Adviser and Certification and Training Scheme (FACTS) qualified adviser. P, K and S were applied at a single rate across all treatments, based on the requirements of the untreated control (Defra, 2010b; SAC, 2010).

2.5 Harvest

Crop yields were measured each year using standard techniques. For cereals, oilseed rape and linseed a small plot combine was used, with grain/seed samples taken from each plot for determination of nutrient (N, P, K, Mg, S) and dry matter contents. Grass yields were measured at first cut (i.e. the first grass cut of the year, typically in May or early June) using a mechanical grass harvester, with samples of the cut grass taken for nutrient analysis (N, P, K, Mg, S). Yields were not assessed at subsequent cuts, although the sites were maintained by periodic cutting/topping depending on grass growth in order to maintain a healthy and productive sward. The potatoes grown at Harper Adams in the first year were harvested by hand, graded and weighed, with nutrient analysis performed on samples of the 45-65mm and 65-85mm size grades only (i.e. the 'ware' or marketable fraction).

In the final year (harvest 2013) more detailed crop quality assessments were undertaken, with harvested crop samples also analysed for grain protein (cereals only), oil content (oilseed rape seed), total metals Zn, Cu, Cd, Pb, Ni, Cr, Hg, As, Se, Mo & F), mycotoxins (deoxynivalenol-DON and zearalenone-ZON at Harper Adams and Devizes only) and titanium content (grassland sites only, as an indicator of the degree of soil contamination of the cut grass).

2.6 Soil quality assessments

In spring 2013, *c.*6 months following the third and final application of treatments, a range of topsoil (0-15 cm) chemical, biological and physical properties were measured at each of the sites as indicators of the impact of the repeated annual applications of organic material additions on soil health and quality (Table 7). This involved taking *c.*5 kg topsoil from each plot for determination of soil chemical properties, microbial biomass, respiration and potentially mineralisable N; taking 3 replicate intact soil cores (0-5 cm depth) per plot for determination of soil bulk density, porosity and water held at field capacity; taking a representative 500 g/plot topsoil sample for determination of water held at 2 and 15 bar, and a 1 kg/plot topsoil sample for determination of aggregate stability. Earthworm populations (3 samples/plot), shear strength (10 vanes/plot), penetration resistance (10 penetrometer readings /plot) and infiltration rates (1 infiltrometer/plot) were determined in the field.

Table 7 Soil quality measurements and methodologies

Soil property	Method
Chemical:	
Organic Carbon (OC)	Modified Walkley Black or 'Tinsley' (MAFF, 1986); where SOM = 1.724 * OC
Loss on Ignition (LOI)	(MAFF, 1986)
Dissolved Organic Carbon (DOC)	Potassium sulphate (taken from the biomass C procedure; Brookes *et al.*, 1985)
Light Fraction Organic Matter (LFOM)	Density separation (Gregorich *et al.*, 1997)
Total Nitrogen (N)	Kjeldahl (MAFF, 1986)
pH	Water (MAFF, 1986)
Extractable Phosphorus (P)	Olsen (MAFF, 1986); Modified Morgan's (SAC, 2010)
Extractable Potassium (K), Magnesium (Mg) and Sulphate (SO_4)	Ammonium nitrate (MAFF, 1986)
Extractable Copper(Cu)	Ammonium EDTA (MAFF, 1986)
Soluble Boron(B)	Hot water (MAFF, 1986)
Cation Exchange Capacity (CEC)	Ammonium acetate (MAFF, 1986)
Total metals/PTEs (Zinc-Zn, Copper-Cu, Cadmium -Cd, Nickel-Ni, Lead-Pb, Chromium-Cr, Mercury-Hg, Arsenic-As, Selenium-Se, Molybdenum-Mo, Fluorine-F)	Aqua regia digestion (MAFF, 1986)
Total Cobalt-Co and Iodine-I (grass sites)	(MAFF, 1986)
Organic contaminants: OCCs (PAHs, phthalates, PCBs, dioxins/furans)	High resolution Gas Chromatography Mass Spectrometry (GCMS)
Biological:	
Biomass C & N	Chloroform-extraction (Brookes *et al.*, 1985). Correction factor = 2.22 (Wu *et al.,* 1990)
Respiration	Alkali (KOH) absorption under controlled laboratory conditions (Anderson & Domsch, 1989)
Potentially Mineralisable Nitrogen (PMN)	Anaerobic incubation (Keeney, 1982)
Earthworms	Hand-sorting a known volume of soil (Schmidt, 2001)
Physical:	
Total Available Water Capacity (AWC) and Easily Available Water Capacity (EAWC)	Volumetric moisture content between 0.05 and 15 bar or 0.05 and 2 bar, respectively (MAFF, 1982)
Bulk Density	Intact soil cores (MAFF, 1982)
Porosity	Porosity = 1-(bulk density/particle density)*100; where particle density=2.65 (MAFF, 1982)
Aggregate Stability	Dispersion ratio on 5-30mm aggregates (MAFF, 1982)
Shear Strength	Field: 'pilcon' shear vane to 7.5 cm (MAFF, 1982)
Penetration Resistance	Field: penetrometer to 15cm (MAFF, 1982)
Infiltration Rates	Field: double ring infiltrometer (MAFF, 1982)

Soil sampling for the biological measurements (microbial biomass, respiration and potentially mineralisable N) were undertaken between March and April 2013, as the soil was warming up, but still moist, according to recommended practice (ISO 10381-6; 2009). This was to ensure each site was sampled under similar conditions to minimise any variations in these biological properties due to fluctuations in temperature and moisture.

2.7 Quality control and data collation

All measurements and experimental work were undertaken following ADAS/SAC internal quality controlled standard operating procedures (SOPs), using a single cross-site protocol to ensure consistency between the experimental sites. Organic material, soil and crop samples were submitted to ADAS selected UKAS accredited laboratories, along with ADAS internal standards to ensure quality control (on top of the laboratories normal in-house quality control processes). Results were checked and collated centrally using Microsoft Excel.

2.8 Statistical analysis

Single site analyses - At each experimental site, the effect of the different organic material treatments on soil quality (as assessed in spring 2013, Table 7), crop yields and quality was evaluated using conventional analysis of variance (ANOVA) and comparison of P-values. A separate ANOVA was carried out at each site, after which *post-hoc* testing was undertaken to evaluate which treatment means were different from each other using a Duncan's multiple range test (using Genstat version 12; VSN International Ltd, 2010). This test assigns different letters to treatment values which are significantly different from each other at the 5% level ($P<0.05$). In the tables of results and graphs, treatments which are statistically significantly different are marked with different letters. For example, if the control treatment result is marked with 'a' and the green compost treatment result with 'b', then these two treatments are different from each other. However, if the digestate treatment result was marked with 'ab', then it is not different from either the control or green compost treatment results

Multiple site analyses (soil quality) - In addition to establishing the effect of the treatments on soil quality at individual sites we were also interested in exploring patterns across all sites in order to establish whether differences observed at the individual sites were consistent across all sites or whether the responses differed with site (soil type & climatic conditions), land use (grass/arable) and prior history (i.e. whether the sites had a previous history of organic material additions, as at Harper Adams and Terrington). The influence of these various factors was therefore investigated using a multipredictor modelling approach, using generalised linear mixed models (GLMMs) or general linear models (GLMs), with experimental 'site' included as a random effect in the former and as a fixed effect in the latter. All models were nested and the manure-based digestate treatment was excluded from this analysis as it only occurred at two sites. The importance of individual predictors within the models (i.e. site, land-use and prior history) was assessed by comparing Akaike's Information Criteria (AIC) values (i.e. a lower AIC value indicated a better fit). Models with different fixed factors were compared (as described below). Whilst comparison of fixed effects using AIC is routinely undertaken in the peer-reviewed scientific literature (Whittingham *et al.* 2005; Whittingham *et al.* 2006; Richards *et al.* 2011) there has been some debate on whether this is good practice (e.g. see on-line forum - http://www.vsni.co.uk/forum/viewtopic.php?p=3276). We have used this approach as it is commonly adopted and advocated (e.g. Verzani, 2014), with the results from the models supported by observed patterns in the data. An improvement in AIC of two or more is sometimes used to indicate a meaningful difference (Burnham and Anderson 2002). However, more recent work has indicated that this value is too liberal, with differences over six suggested as providing strong evidence (Richards 2005; 2008). We therefore used improved fit values of greater than six to indicate a substantially improved fit (*** in Table 9) and values of between two and six as a minor improvement (* in Table 9).

The following models were compared:

(i) Effect of site (i.e. do soil properties vary across the sites?): As 'site' was defined as a random effect this could not be estimated directly. Instead, the effect of site was estimated by comparing AIC values between two general linear models: Model A = $x \sim$ treat; Model B = $x \sim$ treat + site; where x = the response variable (i.e. the soil property in question).

(ii) Effect of treatment (i.e. is there an effect of treatment across all sites?): the AIC between the following two models were compared: Model C = $x \sim 1 + (1|\text{site})$; Model D = $x \sim \text{treat} + (1|\text{site})$.

(iii) Interaction between site and treatment (i.e. does the response to treatment vary across the sites?): the effect of site was estimated by comparing AIC values between two general linear models: Model A = x ~ treat + site; Model B = x ~ treat + site + site*treat; where x = the response variable (i.e. the soil property in question).

(iv) Interaction between treatment and grass/arable (i.e. is the effect of treatment different at the grassland sites compared to the arable sites?): the AIC between the following models were compared: Model G = x ~ treat + grassarable + (1|site); Model H = x ~ treat + grassarable + treat*grassarable +(1|site).

(v) Interaction between treatment and prior history (i.e. is the effect of treatment different at the sites with a history of organic material applications?): the AIC between the following models were compared: Model I = x ~ prior + treat + (1|site); Model J = x ~ prior + treat + prior * treat + (1|site).

Most of the multi-predictor models assumed a normal distribution, with responses transformed to normality as required (e.g. by logging data) although a Poisson error model was used in one case. Model fits were assessed using standard diagnostics such as Quantile-Quantile (QQ) plots.

Multiple site analyses (earthworm populations) – In addition to the statistical analyses outlined above, the earthworm results were also analysed using cross site analysis of variance, with separate models carried out for the five arable sites and the two grassland sites, and post-hoc testing undertaken to evaluate which treatment means were different from each other using a Duncan's multiple range test (using Genstat version 12; VSN International Ltd, 2010). Relationships between earthworm numbers on the untreated control or livestock slurry treatments and those on the food-based digestate treatment were further explored using linear regression.

Multiple site analyses (crop yields) – Cross site analysis of variance was also performed on the crop yields, combining results from across all three harvest years and sites either growing cereals or grass. Post-hoc testing was then undertaken to evaluate which treatment means were different from each other using a Duncan's multiple range test (using Genstat version 12; VSN International Ltd, 2010).

3.0 Results

3.1 Organic material loading rates

Total organic matter (OM) loadings from the organic materials applied over the three year experimental period, together with OM loadings from historic applications (at Harper Adams, Terrington and Aberdeen), are summarised in Table 8. Over the three year *DC-Agri* experimental programme the green compost and FYM treatments supplied similar amounts of organic matter (*c.*16 t/ha equivalent to *c.*9 t/ha organic carbon – OC), the green/food compost *c.*11 t/ha OM (or 7 t/ha OC), livestock slurry *c.* 8 t/ha OM (or 5 t/ha OC) and food-based digestate *c.*2 t/ha OM (or 1 t/ha OC), with differences between the sites a reflection of the different sources and hence composition of the organic materials (which was particularly marked on the green compost treatment at Aberdeen, due to a high OC content of the compost sourced in 2012). The sites at Aberdeen, Harper Adams and Terrington were existing experimental platforms and had benefitted from historic applications of FYM, slurry and green compost (over a 1-17 year period depending on the site; Table 2) and at Harper Adams from food-based digestate applications (for 3 years prior to DC-*Agri*). The recent and previous organic material applications extended the range of OM loadings from *c.*2 t/ha OM up to *c.*105 t/ha OM.

Table 8 Total organic matter loadings (t/ha)[1] at the experimental sites. Results are for the recent three year *DC-Agri* experimental programme (2010-13), plus historic applications where applicable (breakdown between the recent and historic applications given in parenthesis)

Treatment	Aberdeen	Ayr	Devizes	Faringdon	Harper Adams	Lampeter	Terrington
Green compost	24.9 (22 + 2.9)[2]	16.6	17.1	16.3	48.7 (16.5 + 32.2)[3]	15.8	46.8 (16.5 + 30.3)[4]
Green/food compost	15.3 (9.8 + 5.5)[2]	11.6	10.7	9.7	8.9	11.8	12.9
Food-based digestate	1.4	2.2	2.0	1.9	5.3 (1.2 + 4.1)[3]	1.6	2.3
FYM	13.8	14.1	15.5	13.6	105.3 (18.2 + 87.1)[3]	18.0	80.8 (19.1 + 61.7)[4]
Slurry	7.3	6.5	10.8	7.3	44.9 (8.6 + 36.3)[3]	11.8	18.3 (2.1 + 16.2)[4]
Manure-based digestate	6.8	3.1	-	-	-	-	-

[1] To convert to organic carbon multiply by 0.58

[2] Green compost was applied at two rates in 2009 at Aberdeen (Wrap project OAV023-017; Litterick *et al.*, 2009); supplying *c.*3 t/ha OM to the *DC-Agri* green compost treatment and *c.*5.5 t/ha OM to the *DC-Agri* green/food compost treatment.

[3] At Harper Adams, cattle FYM and slurry were applied annually for 16 years prior to *DC-Agri*, supplying *c.*87 and *c.*36 t/ha OM, respectively (Defra project SP0530; Bhogal *et al.*, 2009); green compost was introduced in 2004 and applied for 6 years prior to *DC-Agri*, supplying *c.*32 t/ha OM (SP0530); food-based digestate was applied for 3 years prior to DC-*Agri*, supplying *c.*4 t/ha OM (Charles Murray, pers.comm).

[4] At Terrington, pig FYM and slurry were applied annually for 17 years prior to *DC-Agri*, supplying *c.*62 and *c.*16 t/ha OM, respectively; green compost was introduced in 2004 and applied for 6 years prior to *DC-Agri*, supplying *c.*30t/ha OM (Defra project SP0530).

3.2 Effect of organic material additions on soil quality

Up to 45 different topsoil chemical, biological and physical properties were measured in spring 2013, *c.*6 months following the third and final organic material applications; full results are presented in Appendix 1. At all seven sites, there were no significant (*P* values ranged from 0.10-1.0) treatment effects on topsoil total Ni, Cr, As, (As was border-line at Terrington at *P*=0.06, but here the control soils had the highest As content), Hg, Mo, Co, I and F concentrations or on the concentration of organic contaminants: DEHP (di-(2-ethylhexyl)phthalate), PAHs, dioxins and furans. Similarly, topsoil respiration rates, infiltration rates (both the initial and equilibrium infiltration rate) and the total available water capacity (AWC) did not differ significantly between the organic material treatments (P values ranged from 0.09 to 0.99; Appendix 1).

Results from the multi-predictor modelling revealed a substantially improved model fit when site was included in the model (AIC values improved by >6 in many cases) for nearly all of the measured parameters (Table 9), which was not surprising given the range of soil types and agroclimatic locations (Table 2). However, as well as the underlying baseline soil characteristics, land-use (grass vs. arable) and prior history (i.e. whether there was previous history of organic material additions) also had an impact on the response of some parameters to the treatments applied (Table 9). As the underlying baseline soil conditions varied across the sites, the results have been presented as a percentage difference from the control treatments in order to normalise the data across the different sites and identify the direction of change in soil properties as a result of the organic material additions; treatment means for each of the soil properties for the individual sites are presented in Appendix 1.

Table 9. Summary of multipredictor modelling results performed on data from all sites.[1]

Parameter[2]	Site	Treatment	Treatment x Site	Grass/arable	Prior history
Soil chemical properties					
Organic matter[3]	nd	***[3]	nd	nd	nd
Loss on ignition (LOI)	***	***	N	N	N
Dissolved OC (DOC)	N	N	N	N	N
Light fraction (LFOM)	***	N	***	***	N
Total N	N	***	*	N	N
Ext. P	***	***	N	N	N
Ext. K	***	***	***	N	N
Ext. Mg	N	N	***	***	N
Ext. SO_4[4]	N	N	***	N	***
Soluble B[4]	***	N	N	N	N
pH	***	***	***	***	*
CEC	***	*	N	N	N
Total Zn	***	N	N	N	N
Total Cu	***	*	*	N	*
Ext. Cu	***	***	***	N	***
Total Pb[4]	***	N	N	N	N
Total Cd	***	N	N	N	N
Total Se	***	N	N	N	N
Sum of 7 PCBs	*	*	N	N	N
Soil biological properties					
Microbial biomass C (ln)	***	N	N	N	N
Microbial biomass N (ln)	***	*	***	N	***
PMN (ln)	***	***	N	N	N
Earthworm counts (P)	***	N	***	***	*
Earthworm weights	***	N	***	N	N
Soil physical properties					
Bulk density	N	***	N	***	*
Porosity	***	***	*	***	*
Aggregate stability[4]	***	N	N	N	N
Shear strength (ln)	***	*	N	N	N
Penetration resistance (ln)	***	***	N	N	N
Moisture @ 0.05 bar	***	***	N	***	N
Moisture @ 2 bar	***	*	***	***	N
Moisture @ 15 bar	***	*	***	***	N
Easily AWC	***	*	N	***	N

[1] Models tested for the effect of site, treatment, treatment x site interaction (i.e. is the effect of treatment the same at all sites?), grass/arable (i.e. is the effect of treatment different at grass sites compared to arable sites?); prior history (i.e. is the effect of treatment different at sites with a prior history of organic material additions?). *** strong evidence of an effect (AIC improved by >6); * weak evidence of an effect (AIC improved by 2-6); N – no evidence of an effect (AIC values similar i.e. <2 difference) ; ND – not determined as not possible to fit model due to lack of transformation to normality or other sensible error structure not appropriate); Parameters were untransformed unless indicated (ln = logged) and were fitted with a Gaussian Error Structure unless otherwise indicated (P = Poisson).

[2] There was evidence of the effect of site on total Ni, Cr, As, Hg, Mo, Co, I, F, DEHP, PAHs, dioxins and furans concentrations, respiration rates and infiltration rates (initial rate only), but no effect of any of the other factors testing in the modelling exercise. There were no differences in AWC that could be explained by the models. This confirmed the single site analyses, so these properties have not been included in this table.

[3] Organic matter = organic carbon *1.724; analysed using a non-parametric test (Kruskal-Wallis Test – one-way test of response variable versus treatment but not controlling for site) due to poorly distributed data (***$P<0.001$ in the Kruskal-Wallis Test). [4]Poor model fit (as assessed using standard diagnostics, e.g. QQ-Plots).

3.2.1 Soil organic matter

Soil organic matter levels were highly variable across the sites, such that multi-predictor models could not be fitted and a non-parametric test (Kruskal-Wallis) was used; this indicated a significant treatment effect ($P<0.001$; Table 9). Inspection of the individual site analyses revealed that treatment effects were only evident at the two sites with a prior history of green compost, FYM and livestock slurry applications (i.e. Harper Adams and Terrington, Appendix 1). Here, there was clear evidence that repeated applications of bulky organic materials for 9 years or more increased topsoil organic matter contents (Figure 2), with both green compost and FYM resulting in a *c.*20-25% increase in SOM relative to the fertiliser control treatment, equivalent to an additional 8-10 t/ha SOM in the topsoil (calculated using the measured bulk densities; Appendix 1). Where these materials had been applied for only 3 years (as at the other five experimental sites) and similarly for the green/food compost additions (which were applied for 3 years at all sites) there were small but non-significant increases in SOM (Appendix 1 & Figure 2). The application of organic materials with a low dry matter content (i.e. livestock slurry and digestate) had very little impact on SOM levels (Figure 2) such that even after almost 20 years of repeated livestock slurry additions at Harper Adams and Terrington (supplying up to 45 t/ha OM; Table 8), the 5-10% increase in SOM was not statistically significant (Appendix 1).

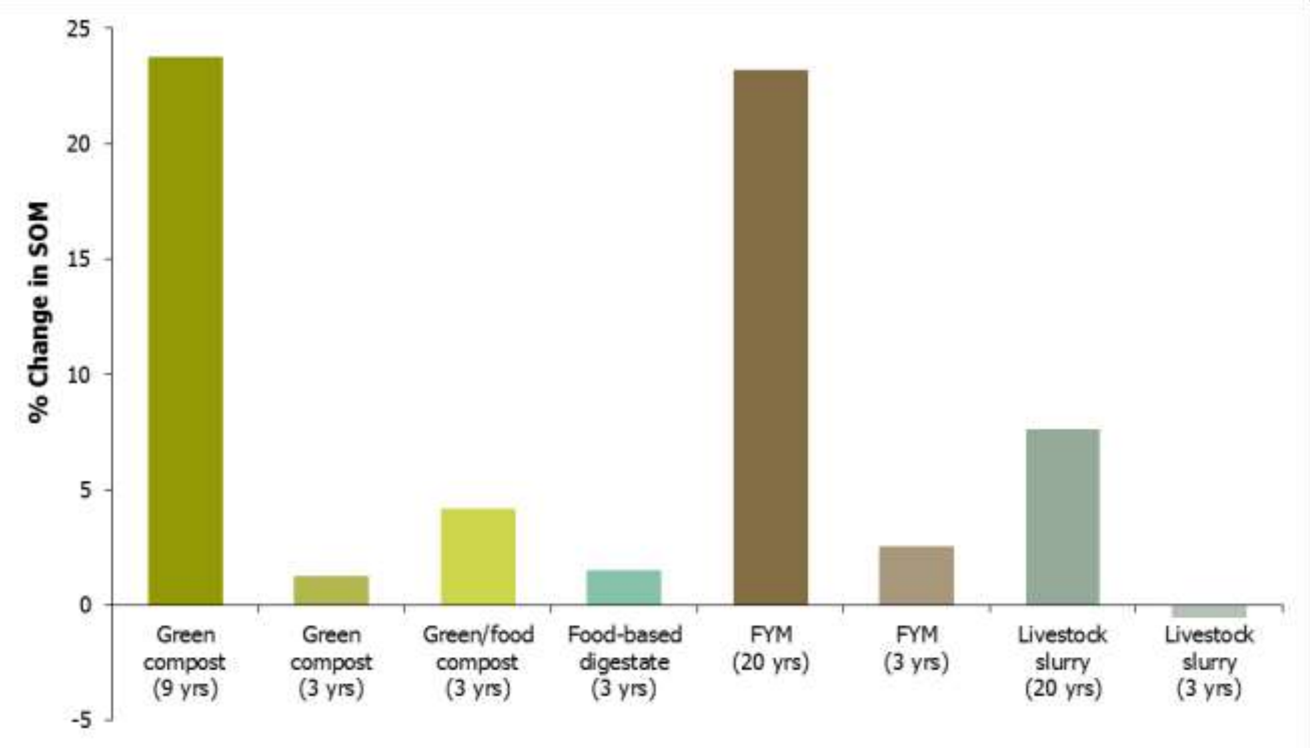


Figure 2 Change in soil organic matter (SOM) following the repeated addition of organic materials for three and over nine years. *Results are expressed as a percentage difference from the control treatment averaged over two sites with a prior history of green compost, FYM & slurry additions, five sites with 3 years of green compost, FYM & slurry additions and seven sites with 3 years of food-based digestate and green/food compost additions. See Appendix 1 for the absolute values at individual sites; significant (P<0.05) treatment effects were observed at Harper Adams and Terrington where FYM and green compost had been applied.*

Although the 9 years of green compost applications supplied only half the organic matter (*c.*50t/ha) that had been supplied by the almost 20 years of FYM applications (80-105 t/ha OM), it resulted in a comparable increase in total SOM levels (10-12 t/ha additional SOM was measured in both treatments). Retention of the OM supplied with the green compost (20-24%) was therefore almost double the retention of OM from FYM (12%), which suggested the green compost was more resistant to decomposition. This was supported by the lignin composition of the applied materials, with the green compost containing *c.*70% lignin compared to *c.*55% in the FYM (Table 5).

There was no overall effect of treatment on the light organic matter fraction (LFOM), although there was a significant site x treatment interaction, with the grassland sites responding differently to the arable sites and no effect of prior history (Table 9). The compost treatments resulted in the greatest increases in LFOM at the arable sites whereas at the grassland sites, both compost and FYM applications resulted in similar increases (Figure 3). However the application of digestate (and livestock slurry at the grassland sites) led to a small reduction in LFOM relative to the fertiliser control (Figure 3). Across all seven sites, the increase in LFOM following the addition of bulky organic materials (i.e. FYM and compost) for 3 or more years was greater (at *c.*30-60%) than the increases measured in the total SOM pool (up to 25%).

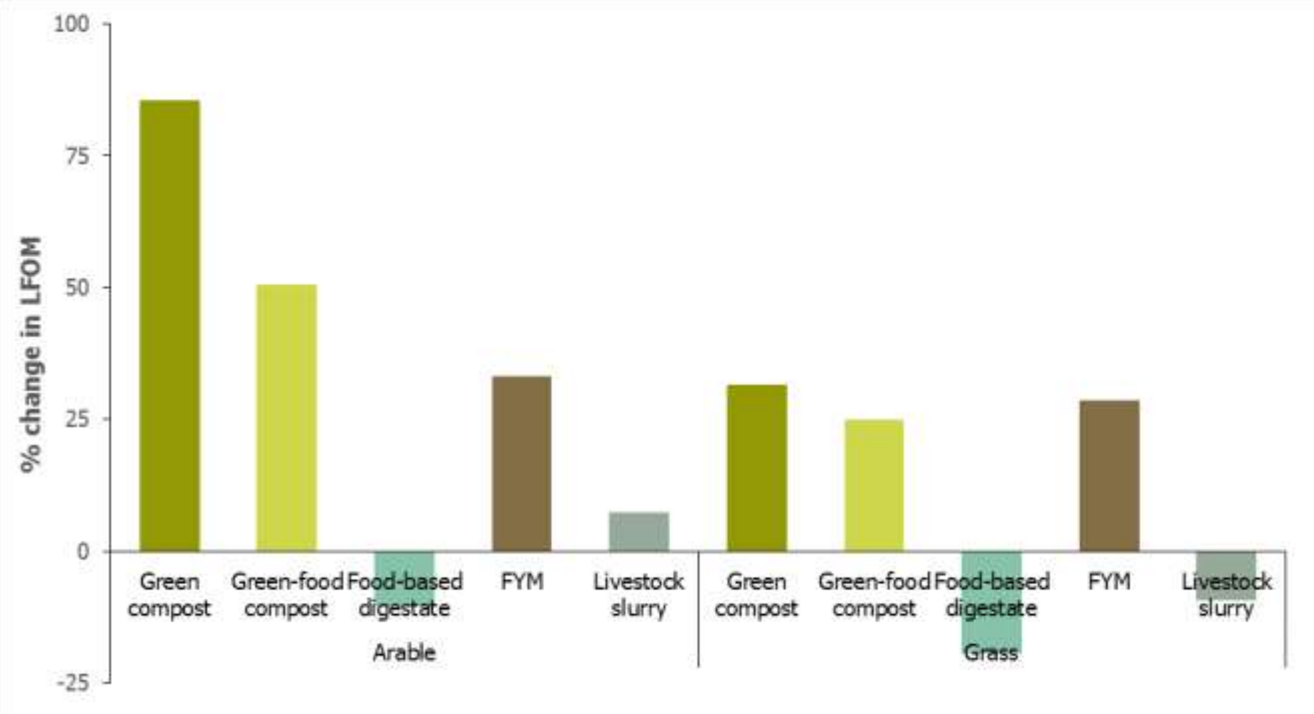


Figure 3 Change in light fraction organic matter (LFOM) following the repeated addition of organic materials at the five arable and two grassland sites. *Results are expressed as a percentage difference from the control treatment averaged over five arable sites and two grassland sites. See Appendix 1 for the absolute values at individual sites. Note there was no effect of prior history, with significant treatment effects observed at 4 of the 7 experimental sites (P<0.05) and marginal effects (P=0.06) at a further two sites.*

3.2.2 Soil microbial biomass

Results from the multipredictor modelling suggested no treatment effect on microbial biomass C, but a strong treatment x site interaction and prior history effect on biomass N (Table 9). The determination of microbial biomass involves analysis of the dissolved organic C and N content of a soil sample before and after fumigation, with the before-and-after difference equating to the microbial biomass. Either the C or N content can be used as a measure of the size of the soil microbial population, with C contents typically larger, but more variable than N (with a microbial C:N ratio ranging between 4 and 8). This variability most likely explains the absence of any overall treatment or prior history effect on microbial biomass C, despite this being clearly evident in the microbial biomass N results. It is also surprising that there was no effect of landuse (grass/arable) both microbial biomass C and N, although there were only two grassland sites compared to five arable sites in the dataset. Inspection of the individual site ANOVAs confirmed the effect of prior history, with increases in both biomass C and N (*P*<0.01) only observed at the two sites (Harper Adams & Terrington) with a prior history of green compost, FYM and livestock slurry additions (Figures 4 & 5). However, although the repeated compost and FYM additions had the same effect on the total SOM pool (increasing it by *c.*25%, despite different total loading rates; Figure 2), the FYM had a proportionally greater effect on the soil microbial biomass increasing it by 50-60% compared to a *c.*20% increase following repeated green compost additions (Figures 4 a & b).

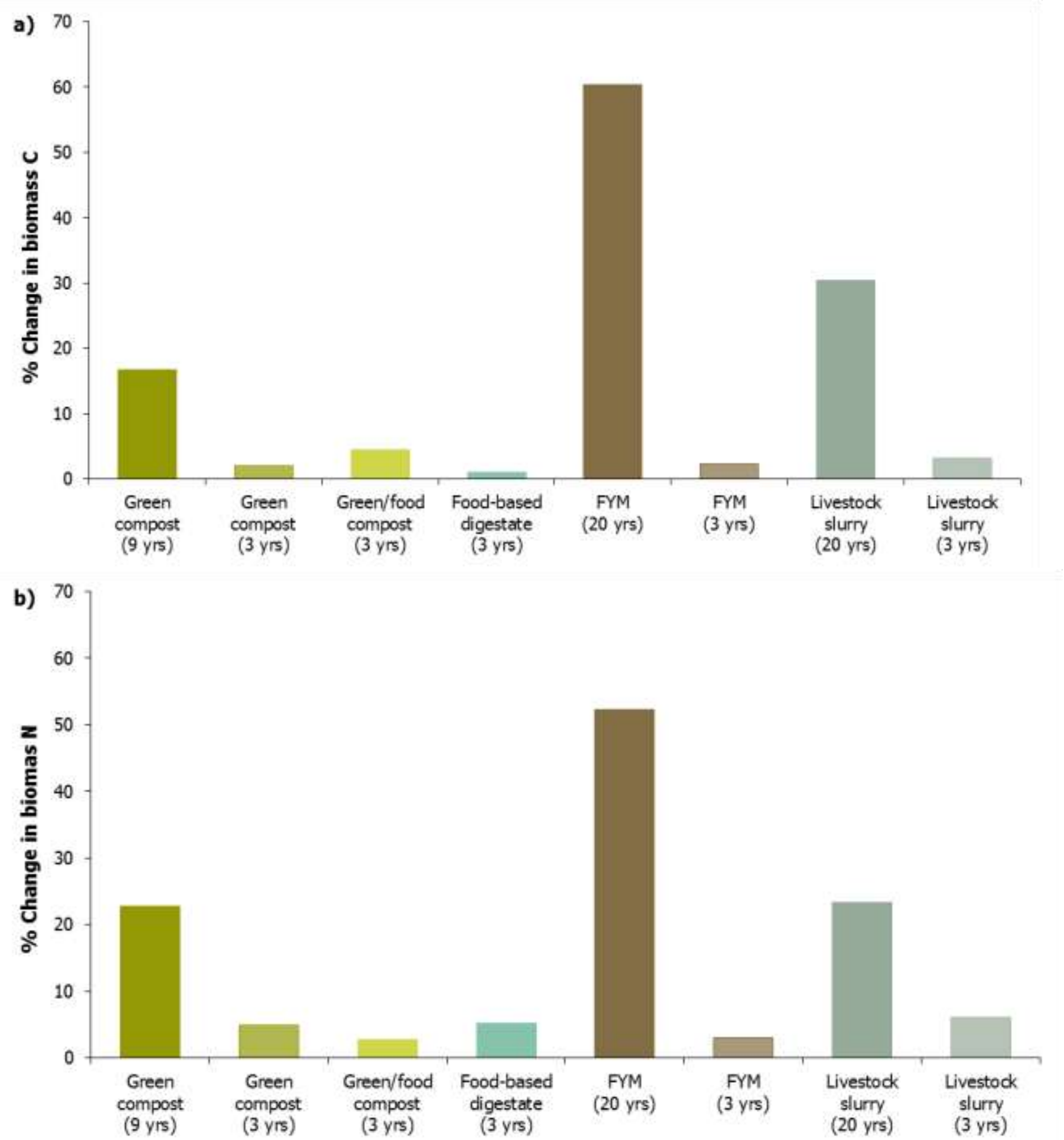


Figure 4 Change in soil microbial biomass carbon (a) and nitrogen (b) following the repeated addition of organic materials for three and over nine years. *Results are expressed as a percentage difference from the control treatment averaged over two sites with a prior history of green compost, FYM & slurry additions, five sites with 3 years of green compost, FYM & slurry additions and seven sites with 3 years of food-based digestate and green/food compost additions. See Appendix 1 for the absolute values at individual sites; significant (P<0.05) treatment effects were observed at Harper Adams and Terrington where FYM had been applied.*

3.2.3 Soil nutrient supply and pH

As expected, the application of organic materials increased soil nutrient supply with improvements in topsoil total N, extractable P and extractable Mg ($P<0.05$ at 4 of the 7 sites for each of these nutrients), extractable K ($P<0.05$ at 6 of the 7 sites), and extractable S ($P<0.05$ at 3 of the 7 sites); Table 10 & Appendix 1). Overall, there was little difference in the response between grass and arable sites, and sites with a prior history of organic material additions (Table 9), which suggested that the addition of organic materials had improved soil nutrient status over a relatively short time-frame (within 3 years). The greatest increases in topsoil nutrient status were following FYM applications, with all organic materials giving rise to significant increases in topsoil extractable K status (which increased by 20-80%; Table 10). Moreover, the capacity of soils to retain and exchange nutrient cations was also improved, as measured by the cation exchange capacity (CEC), with significant treatment effects measured at 2 of the 7 sites (Appendix 1) and weak evidence of an effect across all sites (Table 9). Here, the application of bulky organic materials (green compost and FYM) resulted in the greatest increases (Table 10). This was not surprising given the CEC of a soil is a function of its clay and organic matter (humus) content (i.e. the treatments which increased SOM also increased CEC).

Table 10 Change in topsoil nutrient status and cation exchange capacity (CEC) following the repeated addition of organic materials. *Results are expressed as a percentage difference from the control treatment averaged across all seven sites and excluding the manure-based digestate which was only applied at two of the sites. See Appendix 1 for the absolute values at the individual sites*

Treatment	Total N	Ext. P	Ext. K	Ext Mg	Ext. S	CEC
Green compost	9.1	6.6	33.3	8.3	-3.6	6.7
Green/food compost	6.2	9.8	21.3	-3.1	8.9	3.3
Food-based digestate	2.6	2.4	20.9	-9.2	6.1	1.1
FYM	8.1	36.8	84.3	17.8	15.7	7.0
Livestock slurry	4.2	9.1	48.2	10.1	16.8	0.4

The organic material additions had a significant effect on topsoil pH at four of the seven experimental sites, namely, the two grassland sites and those with a prior history of organic material additions (Appendix 1). This was confirmed by the modelling results which showed strong evidence of a difference between grass and arable sites and weak evidence of a prior history effect (Table 9). At the grassland sites, pH tended to increase where all organic materials had been applied, increasing by 0.3 - 0.5 pH units at Ayr and by 0.2-0.3 pH units at Lampeter ($P<0.05$; Appendix 1). The increases in pH were most likely a reflection of the pH (and neutralising value) of the organic materials (Table 5). The only exception was on the food-based digestate treatment at Lampeter where pH decreased by 0.2 units ($P<0.05$; Appendix 1), which was probably a reflection of the local soil conditions (e.g. buffering capacity & moisture content) in combination with the acidifying effect of the nitrification process as the ammonium-N within the digestate was converted to nitrate-N. At the two arable sites with a prior history, the pH was increased by 0.3-0.5 units on the long-term FYM and livestock slurry treatments (but not the green compost; $P<0.05$; Appendix 1), again most likely reflecting the pH of the applied materials, but only apparent where these materials had been applied for 20 years.

Topsoil potentially mineralisable N (PMN), a biological measure of the soils capacity to supply N through the mineralisation (decomposition) of soil organic N reserves, also increased following FYM and livestock slurry additions at three of the seven experimental sites ($P<0.05$; Appendix 1), with the multipredictor modelling results showing a strong treatment affect which was similar across all sites. There was no improvement in model fit by comparing grass and arable sites or sites with a prior history (Table 9). However, two of the three sites with significant treatment effects were those with a prior history of organic material applications, with the relative increase in PMN (compared to the fertiliser control) most marked where FYM, livestock slurry and green compost had been applied for 9+ years (Figure 5). Again, differences were proportionally greater where FYM had been applied for *c.*20 years (>100% increase) compared to green compost additions over 9 years (*c.*60% increase), despite similar total SOM and nitrogen contents.

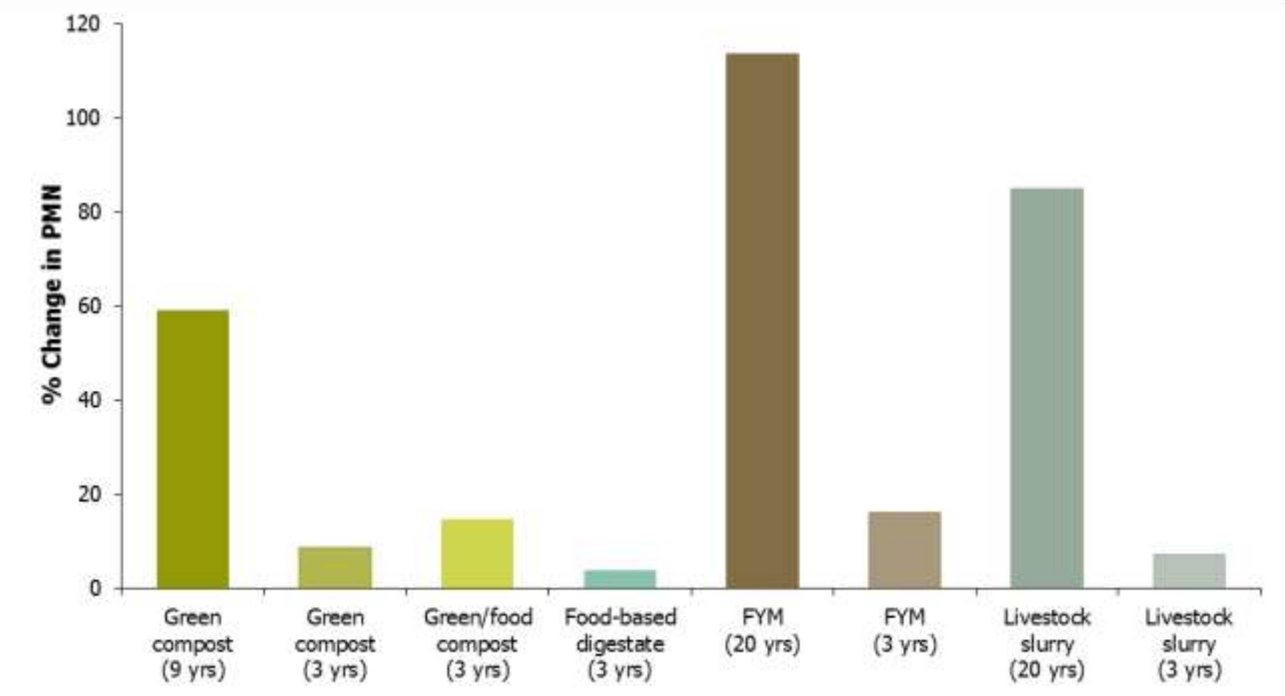


Figure 5 Change in potentially mineralisable nitrogen (PMN) following the repeated addition of organic materials for three and over nine years. *Results are expressed as a percentage difference from the control treatment averaged over two sites with a prior history of green compost, FYM & slurry additions, five sites with 3 years of green compost, FYM & slurry additions and seven sites with 3 years of food-based digestate and green/food compost additions. See Appendix 1 for the absolute values at individual sites; significant treatment effects (P<0.05) were observed at Devizes, Harper Adams and Terrington where FYM and slurry had been applied.*

3.2.4 Soil physical properties

There was a marked improvement in the multipredictor model fits for the variation in topsoil bulk density across the sites due to treatment (i.e. AIC improved by >6), with grassland sites responding differently to arable sites, and a weak improvement in the model fit due to prior history (AIC improved by 2-6; Table 9). At the arable sites, the application of bulky organic materials (i.e. those with a high dry matter content such as FYM and green compost) for 9 or more years resulted in lower bulk densities and consequently higher porosity (porosity is a function of bulk density; Table 7); these treatments also had the highest SOM contents (Figure 2). However, unlike the changes in SOM, the decrease in bulk density was greater following repeated addition of FYM (*c.*8% decrease relative to the control) compared to green compost (*c.*5% decrease relative to the control), despite similar total SOM contents (Figure 6). This was similar to the pattern observed for both microbial biomass and PMN (Figures 4-5.

The topsoil bulk density at the grassland sites responded differently to the applied treatments compared with the arable sites (Table 9). Grassland soils generally have inherently lower bulk densities than arable soils (largely due to higher SOM contents). At both of the grassland sites there were small (*c.*5%) decreases in bulk density following the application of compost and FYM for 3 years, which were statistically significant at Ayr ($P<0.05$) and marginal ($P=0.06$) at Lampeter (Appendix 1). However bulk density increased (and porosity decreased), where organic materials with a low dry matter content had been applied (Figure 7), i.e. the digestates and livestock slurry treatments (including the manure-based digestate applied at Ayr; Appendix 1), although this increase was only statistically significant at Ayr ($P<0.01$) relative to the compost and FYM treatments (not the fertiliser control; $P=0.06$ at Lampeter).

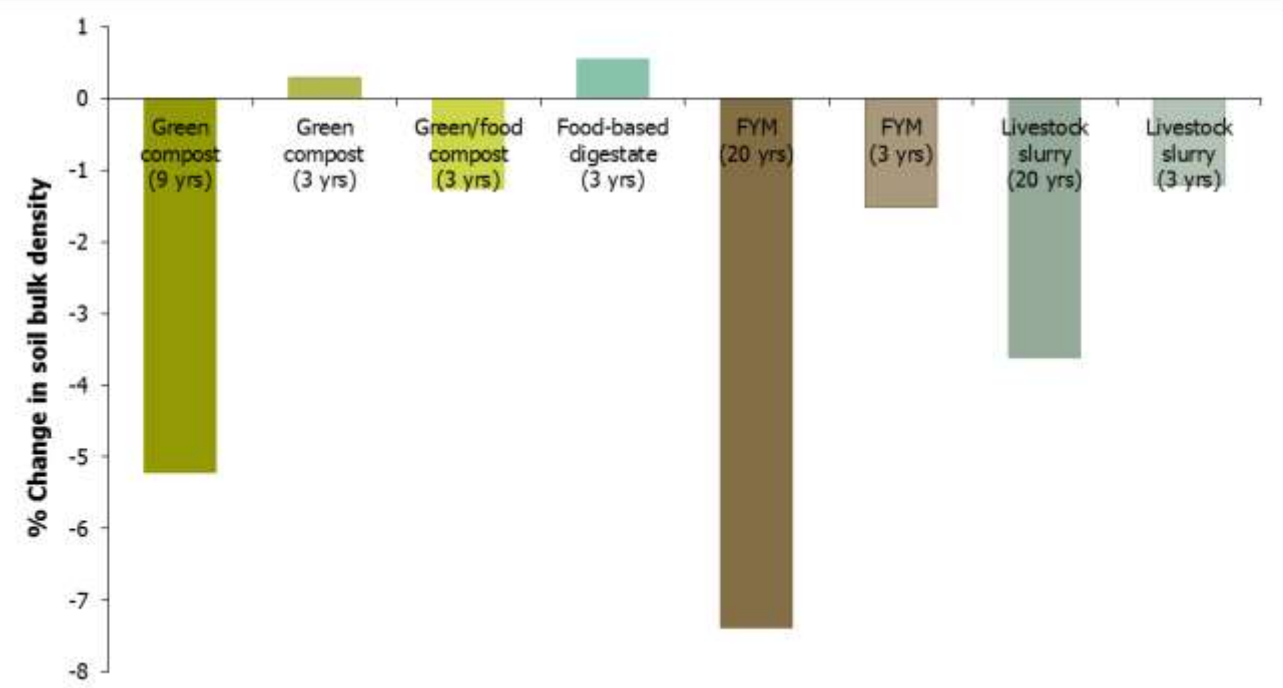


Figure 6 Change in bulk density following the repeated addition of organic materials for three and over nine years at the arable experimental sites. *Results are expressed as a percentage difference from the control treatment averaged over two sites with a prior history of green compost, FYM & slurry additions, three sites with 3 years of green compost, FYM & slurry additions and five sites with 3 years of food-based digestate and green/food compost additions. See Appendix 1 for the absolute values at individual sites; significant treatment effects (P<0.05) were observed at Harper Adams where FYM, green compost and slurry had been applied.*

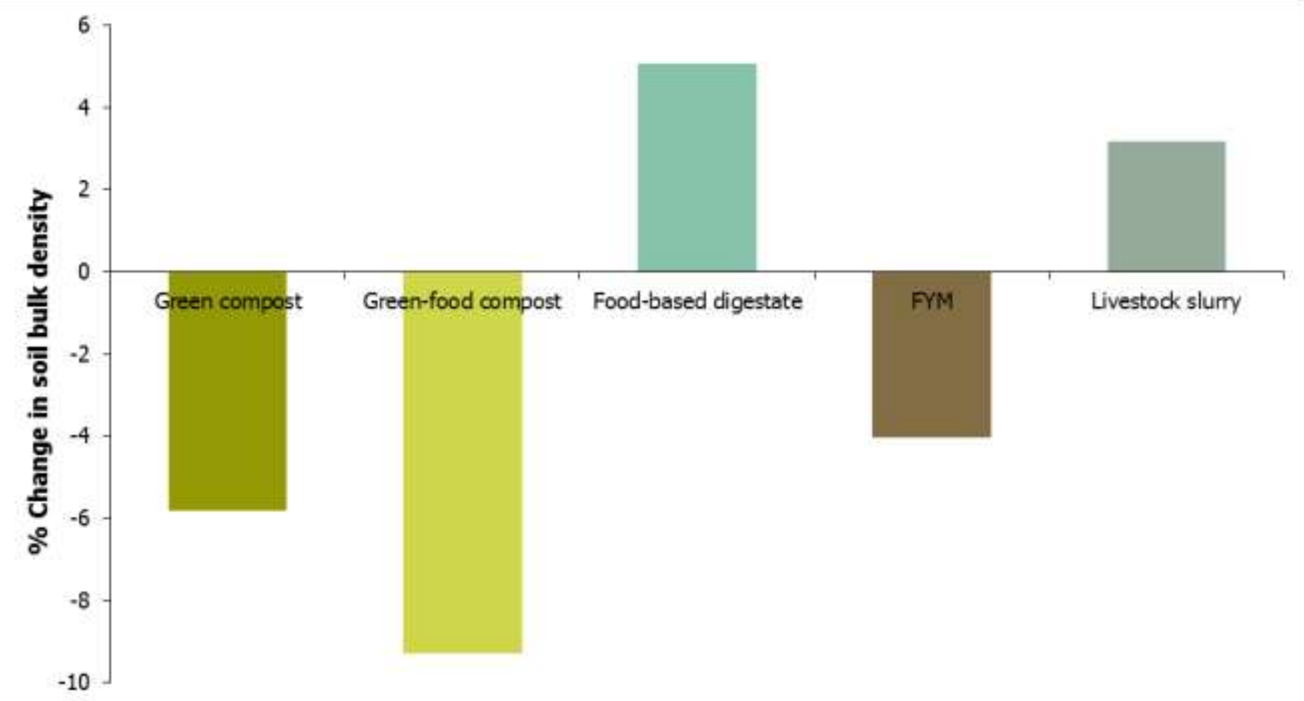


Figure 7 Change in bulk density following the repeated addition of organic materials for three years at the grassland experimental sites. *Results are expressed as a percentage difference from the control treatment averaged over two sites. See Appendix 1 for the absolute values at individual sites; significant treatment effects (P<0.05) were observed at Ayr only (P=0.06 at Lampeter).*

Results from the modelling exercise also revealed a weak effect of treatment on topsoil shear strength (a measure of the force required to work the soil), but no differences between grass and arable sites and no effect of prior history (Table 8). Looking in more detail at the individual site analyses, shear strength decreased at Harper Adams following the application of green compost, FYM and livestock slurry for 9+ years (*P*<0.05 Appendix 1), with no treatment effects observed at the sites where materials had only be applied for 3 years. Again the decrease in shear strength at Harper Adams was greater on the long-term FYM treatment (*c.*20% decrease relative to the control) compared to the long-term green compost and livestock slurry treatments (*c.*10% decrease). By contrast, topsoil shear strength (and penetration resistance) at the Ayr grassland site increased following 3 years of food-based digestate (*P*<0.05 Appendix 1), with no effect of the other organic material treatments.

The decreases in soil bulk density (and increases in porosity) did not, however, lead to statistically significant increases in infiltration rates, although at both Harper Adams and Terrington (sites with a prior history of OM additions), both the initial and equilibrium infiltration rates were numerically higher following 20 years of FYM additions (*P* values ranged from 0.12-0.76 due to high variability in the data set; Appendix 1). Likewise, there was no treatment effect on the total available water capacity (AWC) at any of the sites. However, the multipredictor modelling suggested a significant effect of treatment on the volumetric water content held at field capacity (0.05 bar), 2 bar and 15 bar and the easily available water capacity (EAWC – water held between field capacity and 2 bar pressure), with the model fits markedly improved by taking into account landuse (i.e. grass/arable; Table 9). Inspection of the individual site analyses revealed an increase in the volumetric water content held at field capacity, 2 and 15 bar where FYM and to a lesser extent, green compost had been applied at the Lampeter grassland site (*P*<0.05), but a decrease in EAWC where food-based digestate had been applied at Ayr (*P*<0.05; Appendix 1). These differences were most likely due to changes in bulk density (which was used to calculate the volumetric moisture content). There were no treatment effects on the volumetric moisture contents at the arable sites (*P* values ranged from 0.13 to 0.95, except at Aberdeen where *P*=0.06 for the 2 bar measurement; Appendix 1).

3.2.5 Soil heavy metals and organic contaminants

Repeated organic material applications had very little effect on the concentration of heavy metals in the topsoil, with the inclusion of treatment in the modelling exercise only improving the fit for topsoil total and extractable Cu (Table 9). Here prior history also improved the fit (Table 9). Inspection of the individual site analyses revealed increases in total Cu and extractable Cu concentrations at Terrington due to the application of FYM and livestock slurry (both of which were pig manures). Extractable Cu concentrations were also increased following the application of all organic materials at Harper Adams and green compost, FYM and livestock slurry at Lampeter.

Similarly, there was little effect of the repeated applications of the organic materials on soil organic contaminant compound (OCC) concentrations, with no effect of treatment at any of the experimental sites on the concentration of PAHs, dioxins and furans, and phthalates, and concentrations were low or at the limits of analytical detection (Appendix 1). Treatment had a weak effect on PCB concentrations (Table 9), with concentrations marginally elevated (by 3-5 x 10^{-4} mg/kg dm) at three sites (Ayr, Devizes and Lampeter) where compost (both green and green/food) had been applied compared to the untreated control (*P*<0.01; Appendix 1). However, again PCB concentrations were low at all sites and on all treatments (range: 3-14 x 10^{-4} mg/kg dm).

3.2.6 Earthworm populations

At Ayr, earthworm numbers were significantly lower on food-based digestate treatments in comparison with the fertiliser only control, and all other treatments (*P*<0.05). Notably, of all the sites, Ayr had the greatest number of earthworms (*c.*300-825 compared to 10-70 worms/m^2 on the sandy arable soil at Harper Adams). By way of context, Brady (1974) reported earthworm numbers in arable soils in the range 30-300/m^2, with more than 500/m^2 found in 'rich' grassland soils. There were also significant treatment differences in earthworm numbers between the food-based digestate treatments in comparison with the FYM and livestock slurry treatments at Faringdon; the FYM, livestock slurry and green/food compost treatments at Lampeter; and the green compost and FYM treatments at Terrington ($P<0.05$), but not in comparison with the fertiliser only control treatments at those sites. There were no treatment differences at Aberdeen ($P=0.69$), Devizes ($P=0.21$) or Harper Adams ($P=0.06$); Appendix 1.

Aggregating data across both grassland sites (Ayr and Lampeter), overall earthworm numbers on the food-based digestate treatments were lower than all other treatments ($P<0.001$; Figure 8a), whereas numbers on the green/food compost and FYM treatments were higher than the controls. In contrast, earthworm numbers across the arable sites were similar on all the treatments; although overall earthworm numbers on the FYM treatment were higher than on the control, green/food compost and food-based digestate treatments ($P<0.01$*;* Figure 8b). The multi-predictor modelling confirmed the cross site analysis results for earthworm numbers, with a strong treatment x site interaction, i.e. the treatment effect differed across sites. The model fit was improved when land use (grass/arable) was included as a factor (Table 9) demonstrating the differences between the grass and arable sites. Prior history also had a weak effect (Table 9), with higher earthworm numbers where FYM had been applied for 20 years at Terrington (Appendix 1).

Regression analysis indicated a trend across sites that the more earthworms that were present on the control treatment, the greater the negative impact of the food-based digestate ($P<0.05$; Appendix 2). This general trend existed across all sites, but it was not possible to say whether the rate of reduction (i.e. the slope of the line) was the same for arable and grassland sites since there were only two grassland sites.

Reductions (relative to the fertiliser control) in earthworm biomass (weight) in response to digestate additions were less consistent than those for abundance (numbers). Mean earthworm live weights were calculated as an indicator of shifts in population composition which may influence earthworm numbers. A cross-site (all seven sites) analysis of average live weight per earthworm showed that earthworms from the digestate treatment (*c.*0.42 g) were heavier ($P<0.01$) than from the other treatments (*c.*0.30 g average of all other treatments). The earthworm population abundance to biomass ratio is affected by the balance of adult to juveniles in a population, and the proportions of different species. An increase in average individual earthworm live weight may be due to a population shift towards a greater abundance of adults, an increase in the proportion of larger species within the population or a combination of these factors. Given the six-month gap between treatment and sampling, and the short life cycle of smaller species, a species shift is considered most likely. The impact of the digestate applications may therefore be more pronounced for smaller species and also juveniles due to their greater surface area to mass ratio.

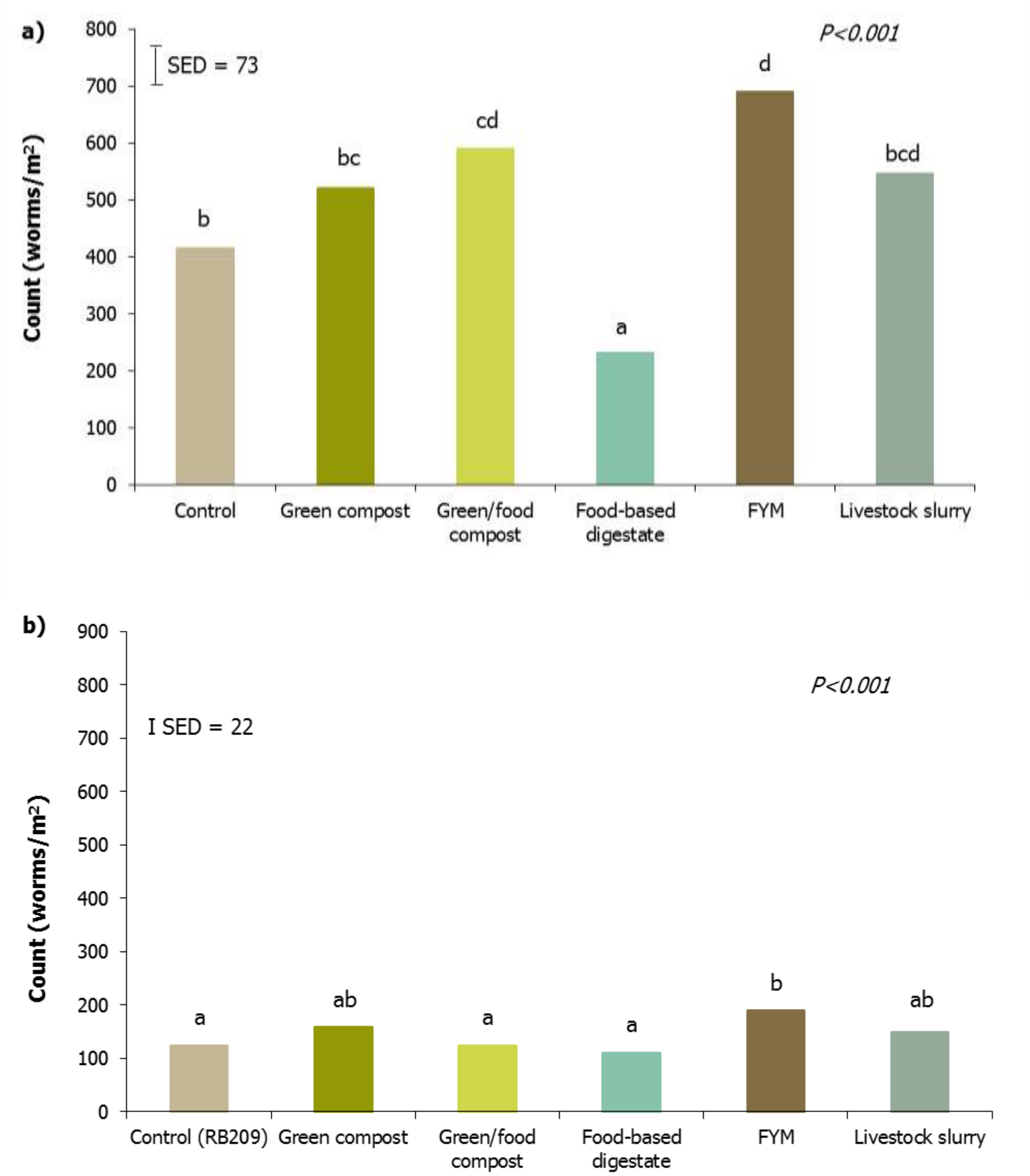
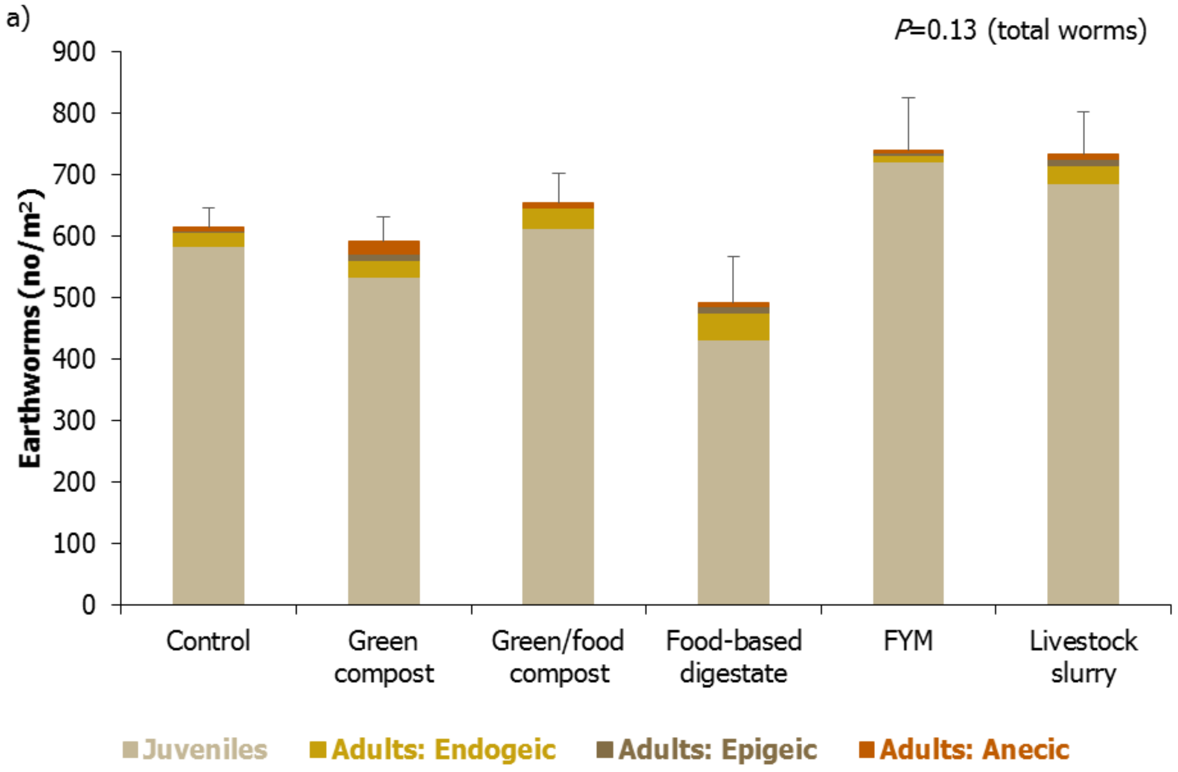


Figure 8 Earthworm numbers (earthworms/m^2 to 25 cm depth) at a) the two grassland sites, and b) the five arable sites. *Standard error of difference between means; Bars labelled with different letters differ significantly (P<0.05; Section 2.8).*

To determine any longer-term effects of the organic material applications on earthworm populations/biomass and communities, additional sampling was undertaken in autumn 2014 to establish whether the treatment differences observed in spring 2013 (*c.*6 months after the final application of organic materials) were still apparent *c.*2 years later. The measurements were undertaken at the four sites where a *significant effect* (*P*<0.05) of food-based digestate application on earthworm numbers/biomass was previously observed (i.e. Ayr, Faringdon, Lampeter and Terrington). The sampling measured endogeic (shallow dwelling) and epigeic (litter dwelling) earthworm populations on 3 'blocks' of soil (each 30 x 30 x 25 cm deep) per plot from the central 2 m x 2 m plot area (i.e. excluding the perimeter plot area to minimise possible earthworm migration effects from adjacent plots) by counting all adult and immature earthworms collected within a *c.*5 minute period. Anecic (deep burrowing) earthworm species were subsequently extracted from the area immediately *below* the three extracted soil 'blocks', using the mustard method (Scullion *et al.*, 2014; Pelosi *et al.* 2014; Clements *et al.*, 2012).

At Ayr there was no statistically significant effect (*P*=0.13) of the organic material additions (last applied in autumn 2012) on total earthworm *numbers* in autumn 2014, although there was a numerical reduction on the food-based digestate treatment (Figure 9a). Moreover, the total earthworm *biomass* in 2014 was significantly reduced (*P*<0.05) where food-based digestate had been applied previously for 3 years (last applied in autumn 2012; Figure 9b). This reduction was confined to the juvenile population only (which represented 80-90% of the total population), with no obvious or consistent differences in the number and biomass of the different functional groups (epigeic, endogeic and anecic) or the species composition of the adult population (full data set presented in Appendix 3; *note* it is not possible to identify juvenile earthworms to a species level based on visual observations).



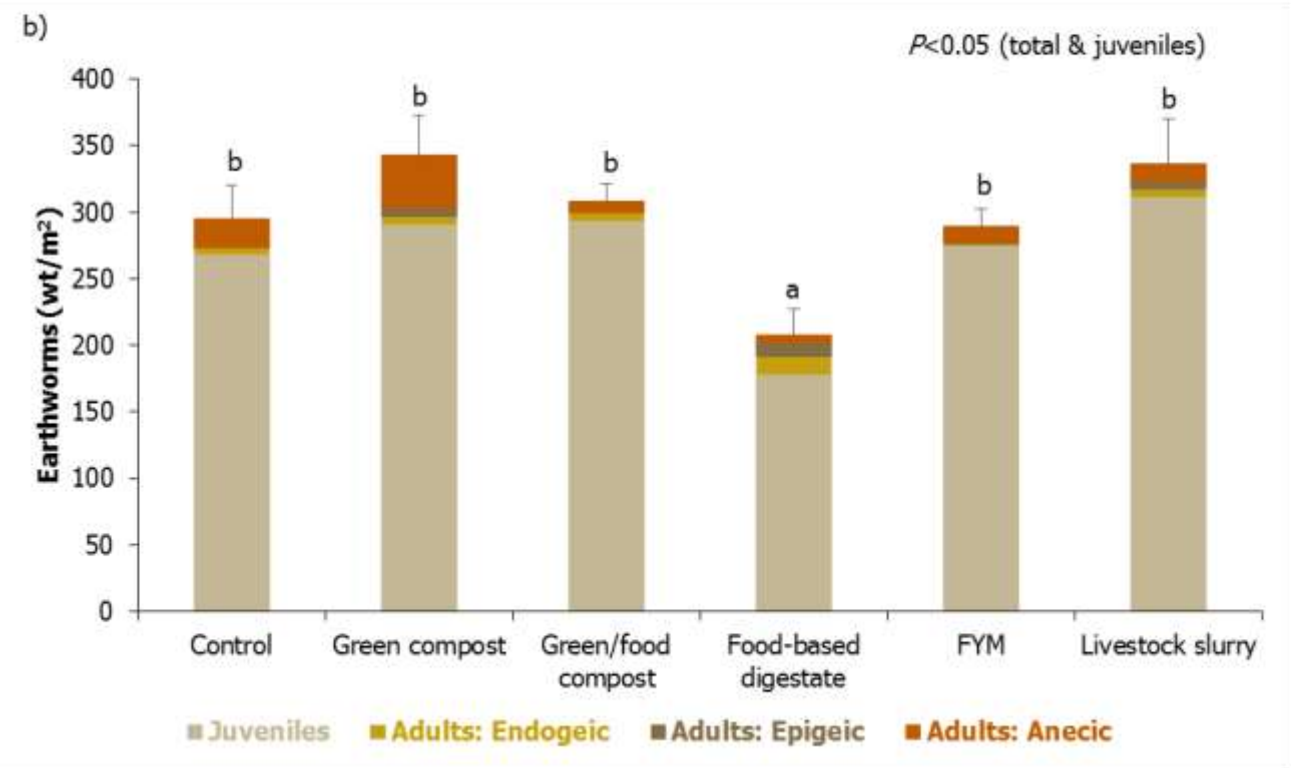


Figure 9. Mean number (a) and weight (b) of earthworms (with standard errors) collected from the Ayr experimental site in autumn 2014. *Bars labelled with different letters indicate significant differences between the total weight of earthworms (P<0.05; Section 2.8), with these differences being due to differences in the juvenile population.*

At the other grassland site (Lampeter), there were no differences in earthworm numbers or biomass as a result of the organic material additions. Similar results were observed on the arable soil at Terrington (Appendix 3). However, at Faringdon, earthworm numbers (but not biomass) were again lowest where food-based digestate had been applied, although these differences were not statistically significant (*P*=0.13; Appendix 3). Earthworm numbers and biomass were highest on the FYM treatment due to an increase in the juvenile population of shallow and surface dwelling species (*P*=0.06 for numbers and *P*=0.05 for biomass; Appendix 3). Again there were no obvious or consistent differences in the species composition of the adult population (Appendix 3).

Scientific and grey literature investigating the impact of livestock manures, biosolids, compost and digestate on earthworm populations and biomass were collated from European studies to contextualise earthworm data from the *DC-Agri* field experiments (Appendix 4). Notably, no studies were found where the impact of food-based digestate on earthworms had been studied; all published studies had used either manure or crop-based digestate. The review identified a number of factors that may have been responsible for the lower earthworm populations/biomass on the food-based digestate treatments compared to the other treatments (including the control), including:

- Ammonium-N (NH_4 / NH_3): organic materials can be transiently toxic to earthworms as a result of the presence of ammonium/ammonia-N in applied organic materials
- pH: in general, earthworms do not thrive in soils with a pH below 5 and are known to be affected by changes in pH e.g. due to manufactured fertiliser nitrogen applications
- Electrical conductivity: high soil electrical conductivity levels can have detrimental effects on earthworms, as a result of exposure to 'salts' (i.e. desiccation).
- Volatile fatty acids (VFAs): although there were no studies on the effects of VFAs on earthworm populations or biomass, food-based digestate typically has a higher overall VFA

content (0.04g COD/g VS) compared to livestock slurry (0.01g COD/g VS), so this was considered to be a potential factor.

- Biochemical oxygen demand (BOD): organic materials with an elevated BOD will deplete oxygen levels in the soil following land application and can potentially have an adverse effect on earthworm populations.

A programme of laboratory experiments was therefore undertaken to determine what factor(s) in food-based digestate were potentially responsible for the differences in earthworm populations observed in the field experiments. These laboratory tests included detailed characterisation of a range of different food-based digestates and cattle slurries, contact tests and pot experiments. Full details of these tests, including methodologies and results are given in Appendix 5. In summary, there was no effect of electrical conductivity (as assessed using contact tests with potassium and sodium chloride solutions) on earthworm mortality. The BOD of a range of digestates was also lower than cattle slurry. These indicated that it was very unlikely that conductivity or BOD were the cause of the earthworm results seen following food-based digestate applications in the field experiments. However the VFA, acetic acid (but not propionic acid), did cause an increase in earthworm mortality in the laboratory contact tests, but only at concentrations in excess of 4,500 mg/l ($P<0.05$). However, further studies using digestate amended with acetic acid showed no effect of increasing concentrations of acetic acid on earthworm mortality up to 5000 mg/l. In the light of these results and the fact that digestate VFA concentrations are typically considerably lower than 5,000 mg/l acetic acid equivalents, VFAs were also ruled out as being the cause of the lower earthworm populations following food-based digestate applications (relative to the fertiliser control) in the field. Ammonium-N was found to have a significant effect ($P<0.05$) on earthworm survival and health, both in the laboratory contact tests (conducted at a constant temperature of 20°C in the dark) and pot studies (conducted at 10-15°C in a temperature controlled greenhouse; Appendix 5). However, there was only a marginal effect of pH, with mortality and health slightly improved at the lower pHs (i.e. when a greater proportion of the applied N was in the ammonium-N form, rather than the ammonia form). Statistical analysis of the results from the pot experiments showed that ammonium-N loadings most strongly explained the negative effects observed (which were a function of both the ammonium-N concentration and the application rate).

This conclusion is also consistent with the results of the original field experiments, where annual ammonium-N loadings ranged from 140-235 kg/ha from the food-based digestate, compared to 62-145 kg/ha from the livestock slurries. Moreover at Ayr, where earthworm numbers were significantly lower than the fertiliser control, the ammonium-N loading from food-based digestate was amongst the highest applied at any site.

3.3 Effect of organic material additions on crop quality

3.3.1 Crop yield and nutrient content

Crop yields (Table 11) and the nutrient (N, P, K, Mg, S) content of the harvested materials (Appendix 6) were measured every year from 2011 to 2013 at each of the 7 experimental sites. As can be seen from Table 11, the number of sites where there were significant ($P<0.05$) treatment effects on crop yields increased over this time period, from just one site (Terrington – winter wheat) in 2011 to 4 sites (Aberdeen – oilseed rape, Devizes – winter wheat, Harper Adams – winter wheat and Lampeter - grass) in 2013 (P values in bold type; Table 11). On the whole, these differences reflected an increase in yield as a result of the organic material additions, with none of the treatments giving rise to significantly lower yields relative to the fertiliser control. Indeed, even where statistically significant differences were not found ($P>0.05$), the yields of most crops in virtually all years were numerically elevated above the control where organic materials had been applied (results in shaded boxes; Table 11), with the exception of linseed at Devizes and grass at Lampeter in 2011 and oilseed rape at Terrington in 2013. This is clearly demonstrated in a cross-site analysis of the winter cereal yields (8 site/seasons), where grain yields increased by 10% on the FYM and digestate treatments relative to the control, by 9% on the livestock slurry treatment, by 8% on the green/food compost and by 7% on the green compost treatment, amounting to 0.5-0.6 t/ha (*P*<0.001; Figure 10). For grass, the cross-site analysis of variance was not statistically significant, despite first cut grass yields being on average, 0.4 t/ha greater where green compost and FYM had been applied (average of 6 site/seasons; Figure 11).

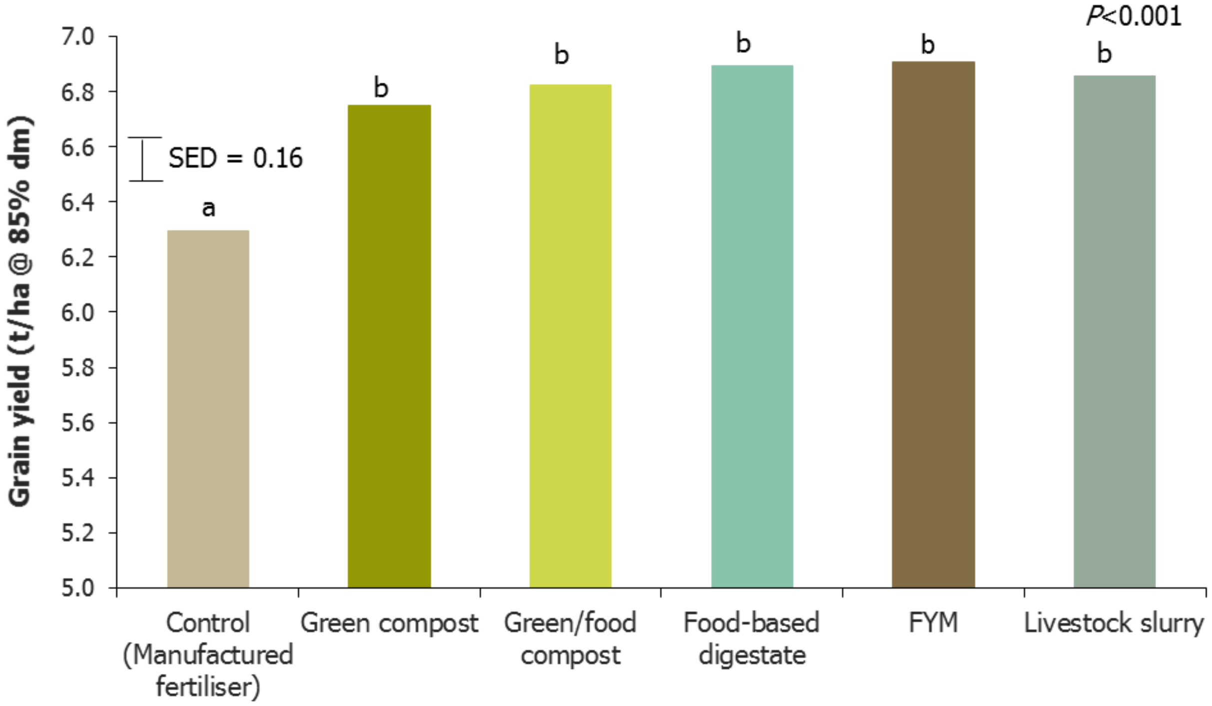


Figure 10 Average winter cereal yields from 2011-2013 at the soil quality experimental sites (results are an average across 8 site/seasons). *Bars labelled with different letters indicate significant differences between treatments (P<0.05; Section 2.8). Results exclude yields on the livestock slurry treatment at Terrington in 2011 (see footnote to Table 11).*

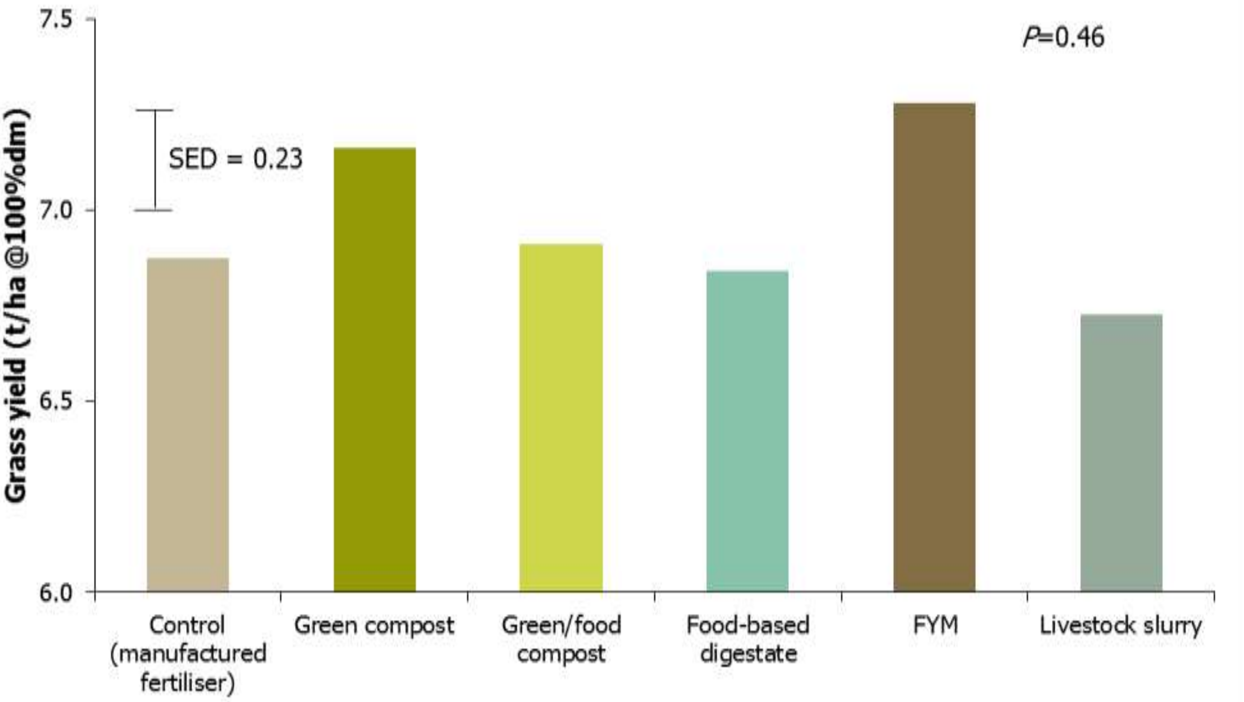


Figure 5 Average first cut grass yields at Ayr and Lampeter from 2011-2013. *Results are an average of 6 site seasons, excluding the FYM treatment at Ayr in 2012.*

Table 11 Crop yields at harvests 2011-2013 (treatment means; n=3). Grass yields are for first cut only. Results that were statistically significant are in bold type; crop yields in shaded boxes are numerically higher than the control.

Treatment	Aberdeen	Ayr	Devizes	Faringdon	Harper Adams	Lampeter	Terrington
Crop 2011^{1}:	**SB t/ha @85% dm**	**G t/ha @100% dm**	**LIN t/ha @100% dm**	**WW t/ha @85%dm**	**POT t/ha FW**	**G t/ha @100%dm**	**WW t/ha @85%dm**
Control	5.60	6.47	3.40	10.4	42.0	9.21	8.05^{a}
Green compost	5.79	7.02	3.39	10.7	35.3	8.88	8.15^{ab}
Green/food compost	5.97	6.62	3.07	10.9	40.5	8.36	7.42^{a}
Food-based digestate	5.87	6.25	3.20	11.2	44.8	8.67	7.55^{a}
FYM	5.94	7.16	3.14	10.3	43.5	8.49	9.30^{b}
Livestock slurry	5.80	5.83	3.04	11.1	45.9	7.45	10.5^{c}
Manure-based digestate^{2}	6.29	5.93	-	-	-	-	-
***P*^{3}**	*NS 0.48*	*NS 0.18*	*NS 0.20*	*NS 0.21*	*NS 0.59*	*NS 0.12*	***<0.001*^{4}**
Crop 2012^{1}:	**WB t/ha @85% dm**	**G t/ha @100% dm**	**WW t/ha @85%dm**	**WW t/ha @85%dm**	**SB t/ha @85%dm**	**G t/ha @100%dm**	**WW t/ha @85%dm**
Control	4.92	5.77^{bc}	8.02^{a}	2.96	2.74	9.28	6.54
Green compost	5.51	5.63^{b}	8.73^{b}	3.02	2.82	10.6	7.36
Green/food compost	6.00	5.94^{cd}	8.77^{b}	3.54	3.01	9.75	7.05
Food-based digestate	5.84	6.26^{e}	8.43^{ab}	3.24	3.09	9.77	7.17
FYM	5.23	5.26^{a}	8.66^{b}	3.22	2.80	9.62	6.85
Livestock slurry	5.12	5.79^{bc}	9.46^{b}	3.65	2.57	9.98	7.22
Manure-based digestate^{2}	6.48	6.09^{de}	-	-	-	-	-
***P*^{3}**	*NS 0.29*	***<0.001*^{5}**	***0.007***	*NS 0.33*	*NS 0.90*	*NS 0.81*	*NS 0.54*
Crop 2013^{1}	**WOSR t/ha @ 91% dm**	**G t/ha @100% dm**	**WW t/ha @85%dm**	**WC t/ha @100% dm**	**WW t/ha @85%dm**	**G t/ha @100%dm**	**WOSR t/ha @ 91% dm**
Control	4.27^{ab}	6.51	5.17^{a}	7.08	4.29^{a}	4.00^{a}	4.51
Green compost	4.55^{bc}	6.69	5.90^{b}	8.05	4.34^{a}	4.18^{abc}	4.21
Green/food compost	4.58^{bc}	6.50	5.87^{b}	7.71	4.95^{ab}	4.29^{bc}	4.26
Food-based digestate	4.55^{bc}	6.02	5.71^{ab}	6.82	4.96^{ab}	4.05^{ab}	4.31
FYM	4.19^{ab}	6.70	7.38^{d}	7.42	5.85^{b}	4.43^{cd}	4.08
Livestock slurry	4.01^{a}	6.71	6.65^{c}	7.67	4.82^{ab}	4.60^{d}	4.31
Manure-based digestate^{2}	4.78^{c}	6.54	-	-	-	-	-
***P*^{3}**	***<0.009***	*NS 0.11*	***<0.001***	*NS 0.22*	***0.05***	***<0.002***	*NS 0.60*

[1] SB: Spring barley-grain; WB: Winter barley-grain; G: Grass @first cut; LIN: linseed-seed; WW: Winter wheat grain; POT: Potato tuber yield – total marketable yield (size classes 45-65mm + 65-86mm); WC: Whole crop oats & peas.

[2] Manure digestate only evaluated at Aberdeen and Ayr.

[3] Statistical analysis undertaken using ANOVA (data normally distributed). There were three replicates of each treatment; *NS:* No significant difference (*P*>0.05). Numbers with a column that are labelled with different letters indicate significant differences between treatments (*P*<0.05; Section 2.8).

[4] Planned livestock slurry application rate was 60m^{3} but the actual application rate was 100m^{3}; this led to an underestimation of the slurry N supply and consequently a higher rate of manufactured fertiliser N was applied. Therefore total (plant-available) N supply to the livestock slurry treatment was greater than for the other treatments.

[5] The FYM treatment did not receive an early N application (unlike the compost treatments) and only received a main dressing of N fertiliser alongside all treatments in late April 2012. This probably led to the significantly lower yields measured on this treatment.

Crop available nitrogen inputs were balanced across the treatments as far as practically possible (based on MANNER-*NPK* predictions of crop available N supply from the applied organic materials), although there were two instances where an imbalance in N supply clearly had an impact on crop yields, due to differences in the overall rate (Terrington in 2011 for the livestock slurry treatment, Table 11) or timing of N supply (Ayr in 2012 for the FYM treatment, Table 11).

Only a single rate of manufactured P, K and S fertiliser was applied at each site (based on the soil analysis for the control treatment and local site conditions), so the supply of these nutrients from the organic materials was in addition to crop requirement. This ranged from 29 kg P_2O_5/ha/yr, 92 kg K_2O/ha/yr and 16 kg SO_3/ha/yr where food-based digestate had been applied, to 159 kg P_2O_5/ha/yr 294 kg K_2O/ha/yr and 193 kg SO_3/ha/yr where FYM had been applied (Table 6). It is therefore likely that much of the measured yield increases were mainly due to an enhanced supply of P, K and S from the organic material additions, rather than a longer-term OM benefit. This is supported by the results from the nutrient analysis of the harvested materials (which show differences in plant P, K and S concentrations; Appendix 6), and can be most clearly seen in 2012 when virtually all the organic material treatments at every site out-yielded the manufactured fertiliser control (Table 11).

For example at Devizes in 2012, where winter wheat yields were increased by 5-18% (0.4-1.4 t/ha; Figure 12a), grain phosphorus concentrations were also elevated where organic materials had been applied ($P<0.05$; Figure 12b), despite an overall maintenance application (i.e. to all treatments) of phosphate fertiliser according to RB209 recommendations for a P Index 2 soil (Defra, 2010b). As the soil at Devizes is a shallow soil over chalk (pH 8), this response to additional P inputs is not surprising, given the P-fixing nature of these soils. At Aberdeen in 2012, winter barley yields increased by 4-32% where organic materials had been applied (0.2-1.6 t/ha – although not statistically significant; Figure 13a). Here, these yield differences were attributed to differences in S supply; no manufactured S fertiliser was applied, which on this sandy loam soil (*c.* 60% sand) resulted in S deficiency on the control treatment, with grain N:S ratios ≥ 17:1 indicating deficiency symptoms (HGCA, 2014a; Figure 13b). Finally, increases in grass yields at Lampeter in 2012 (0.3-1.3 t/ha, although not statistically significant; Figure 14a) were attributed to difference in potash (K) supply (Figure 14b), despite an overall application of potash fertiliser according to RB209 recommendations for first cut silage on a K Index 1 soil (note: the target K index for grass is Index 2-).

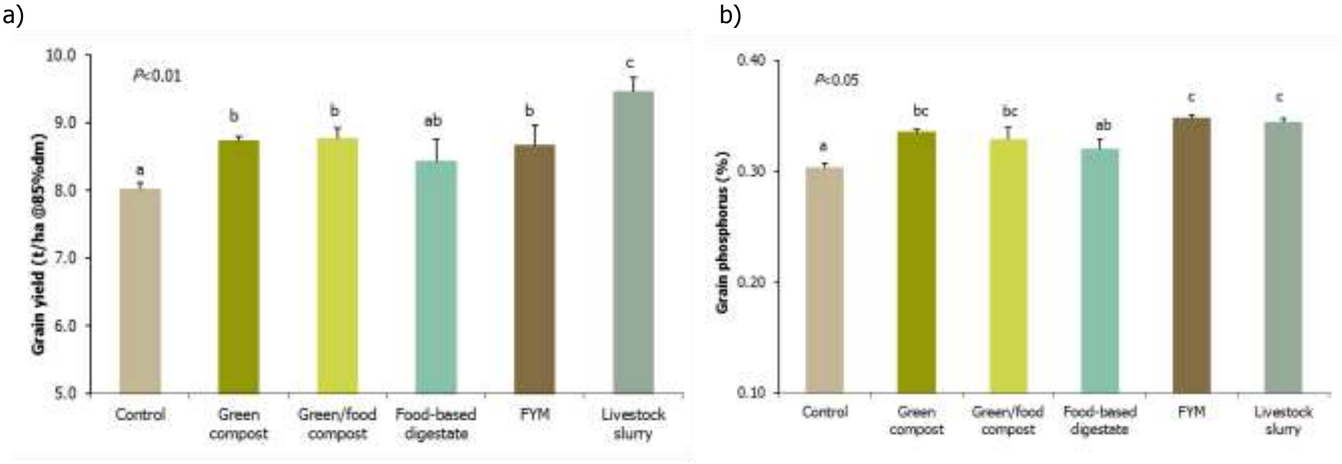


Figure 6 Winter wheat grain yields (a) and phosphorus concentrations (b) at Devizes in 2012 (with standard errors). *Bars labelled with different letters indicate significant differences between treatments (P<0.05; Section 2.8).*

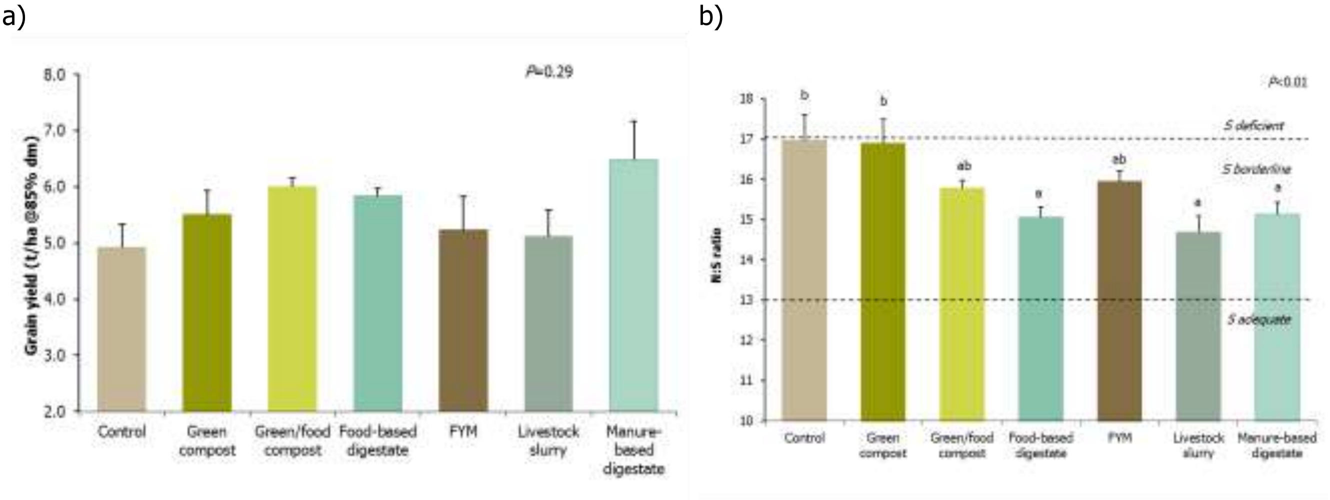


Figure 7 Winter barley grain yields (a) and N:S ratios (b) at Aberdeen in 2012 (with standard errors). *Bars labelled with different letters indicate significant differences between treatments (P<0.05; Section 2.8).*

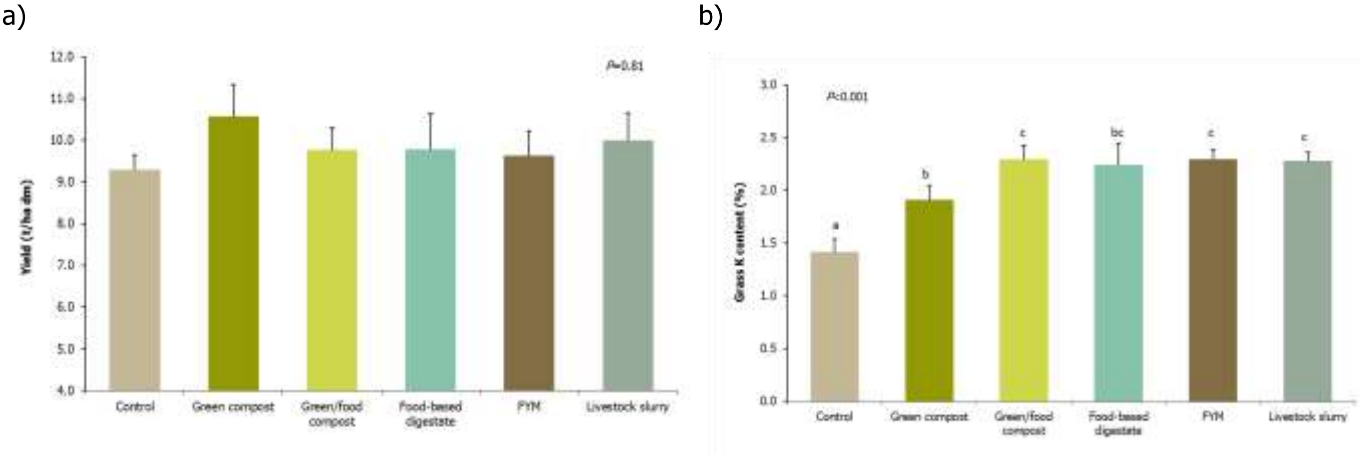


Figure 8 First cut grass yields (a) and potassium content (b) at Lampeter in 2012 (with standard errors)**.** *Bars labelled with different letters indicate significant differences between treatments (P<0.05; Section 2.8).*

3.4 Crop quality

The effect of repeated organic material additions on crop quality was assessed at harvest 2013. This included determination of the specific weight, protein and mycotoxin content of cereal grain at Devizes and Harper Adams, the oil content of rape seed at Aberdeen and Terrington, the titanium content of grass at Lampeter and Ayr and the total metal content of all harvested materials at each site.

The specific weight of cereal grain is related to its quality and nutritional value, such that grain with lower specific weight values usually commands a lower price in the market. Thin, shrivelled wheat grain will not mill to produce adequate amounts of clean, white flour. The specific weight test measures the weight of grain (in kilogrammes) that can be packed into a cylinder of fixed volume (usually 1 litre). If specific weight requirements are not met this can lead to price reductions or grain being rejected. The specific weight of winter wheat grain at Devizes was higher where FYM and cattle slurry had been applied ($P<0.05$; Table 12), reflecting the differences in overall grain yield at this site (Table 11) which were considered to be due to differences in P supply. The specific weight of grain at Harper Adams was also numerically higher on the long-term FYM treatment, although these differences were not statistically significant and grain weights at both sites were lower than the national average value for winter wheat in 2013 of 77.0 kg/hl (range 71-83 kg/hl; HGCA, 2013). Both sites grew bread-making varieties, which as a general rule require high protein contents (13% protein or 2.3% N on 100% DM basis), and as grain protein contents at optimum N fertiliser applications are typically 12%, this often requires additional N inputs (HGCA, 2009). Grain protein at Devizes was in excess of 13% on all treatments, with no effect of the organic material additions (*P*=0.69; Table 12). Protein contents were lower and marginal for bread making at 12.7-13% at Harper Adams, with again no effect of the organic material additions (*P*=0.88; Table 12). As grain protein is largely influenced by N input and N additions were balanced across all the treatments, the absence of any treatment differences is not surprising.

Table 12 Winter wheat grain quality at Devizes and Harper Adams in 2013.

Treatment	**Specific grain weight (kg/hl @85% dm)**		**Grain protein (%)**		**Zearalenone (ZON, µg/kg FW)**	
	Devizes	**Harper Adams**	**Devizes**	**Harper Adams**	**Devizes**	**Harper Adams**
Control	71.9^{a}	75.3	13.8	13.0	1.2	5.4
Green compost	72.6^{ab}	74.4	13.9	13.0	1.8	2.5
Green/food compost	74.0^{abc}	74.5	14.2	12.9	1.8	2.3
Food-based digestate	73.4^{abc}	74.8	13.8	12.7	0.5	2.0
FYM	76.1^{c}	77.6	13.5	12.7	1.2	6.3
Livestock slurry	74.8^{bc}	73.6	13.7	12.7	2.2	9.8
***P*[1]**	***0.05***	***NS (0.33)***	***NS (0.69)***	***NS (0.88)***	***NS (0.54)***	***NS (0.08)***

[1] Statistical analysis undertaken using ANOVA (data normally distributed). There were three replicates of each treatment; NS: No significant difference (*P*>0.05); different letters indicate significant differences between treatments (*P*<0.05; Section 2.8).

The grain from Devizes and Harper Adams was also analysed for the presence of mycotoxins. These are toxic chemicals produced by specific fungi which infect crops either in the field by *Fusarium* species or during storage by *Penicillium* species. The most common *Fusarium* mycotoxins of concern are deoxynivalenol (DON) and zearalenone (ZON), and there are legal limits for both of these toxins in wheat intended for human consumption (1250 µg/kg DON & 100 µg/kg ZON; EC/1881/2006) and guidance limits for feed grain (8000 µg/kg DON & 2000 µg/kg ZON; EC/576/2006). Concentrations of DON were below the detection limit of 0.05 mg/kg on all treatments at both sites and although ZON was detected on all treatments (including the control), concentrations were considerably lower than the limits set for grain intended for both human and animal consumption (Table 12).

Most buyers of oilseed rape in the UK pay an oil premium of 1.5% for every 1% of oil content above 40%, with a similar deduction made for contents below 40%. The oil content of the winter oilseed rape crops grown at Aberdeen and Terrington ranged from 42-44% with no difference between the treatments (*P*=0.95) at Aberdeen and only marginal differences (*P*=0.07) at Terrington (where oil contents were highest on the food-based digestate treatment; Appendix 6).

The titanium (Ti) content of the cut grass at Ayr and Lampeter was analysed as an indicator of the potential for soil contamination of the herbage. This is obviously important where organic materials have been applied as these too could 'contaminate' the herbage and consequently reduce silage quality. There were no differences in grass Ti concentrations at Lampeter (*P*=0.26) and at Ayr Ti concentrations were higher (*P*=0.05) on the control and green/food compost treatments (at *c*.3 mg/kg) compared to the food-based digestate and FYM treatments (at *c*.2.5 mg/kg). There were however, no differences in soil concentrations of Ti (*P*=0.29 at Ayr and 0.26 at Lampeter; Appendix 6).

The metal concentrations of the harvested materials are presented in Appendix 6. Some metals are essential for crop growth (i.e. trace elements), albeit at low levels (e.g. Zn, Cu & Mo), whilst others (e.g. Cd and Pb) can be toxic to plants and humans at high concentrations (i.e. potentially toxic elements), however if present at highly elevated concentrations, the trace elements can also be toxic to plants and animals (e.g. Zn, Cu). The EU has set limit values for these potentially toxic elements in cereals for human consumption (EC/1881/2006) as follows: barley (0.1 mg Cd/kg fw), wheat (0.2 mg Cd/kg fw), all cereals (0.2 kg Pb/kg fw). For grass, the availability of Co, Cu and Se does not restrict growth, but too little in the grazed crops can lead to deficiency in some animals. Moreover, high levels of Mo in grass can induce Cu deficiency in the grazing animal. There was no significant treatment effect on the metal content of the oilseed rape seed at Aberdeen (P=0.15 - 1.0) or the winter wheat grain at Harper Adams (P=0.23 – 1.0; Appendix 6). At the other arable sites, there were significant treatment effects (P<0.05; Appendix 6) on the Cu (Devizes wheat & Faringdon oats), Ni (Faringdon oats, Terrington oilseed rape) and Se (Terrington oilseed rape) content of the harvested products, often reflecting differences in yields at these sites (with lower concentrations where organic materials had been applied, in comparison with the fertiliser only control, due to higher yields resulting in a dilution of the background grain metal content). At the grassland sites the Mo content of the grass was elevated where compost (Ayr) and FYM (Lampeter) had been applied (P<0.01; Appendix 6), with concentrations ranging from 0.4 to 0.7 mg/kg on the untreated control increasing to 1-1.5 mg/kg where compost or FYM had been applied for 3 years. However, these levels are not concerning as they remain within the generally accepted Mo herbage concentration limit of <2mg/kg dm (Rogers, *et al.,* 2000), which is generally considered necessary to avoid Mo-induced Cu deficiency in grazing livestock.

4.0 Discussion

4.1 Soil quality

The beneficial effects of repeated applications of a range of organic materials to agricultural soils (farmyard manures, composts, biosolids etc.) on SOM and soil quality has been widely documented and reviewed (e.g. Bhogal *et al*., 2009, 2011; Edmeades, 2003; Johnston *et al.,* 2009). The results from *DC-Agri* provide further field evidence of this, with some soil properties such as nutrient status (N, P, K, Mg, S), responding to all organic material additions (both solid and liquid) within a short timescale (<3 years), but other properties, such as total SOM, microbial biomass and selected soil physical properties only changing to a statistically significant extent after multiple applications (9 or more years) of bulky organic materials (compost and FYM). Application of organic materials with a low dry matter content (digestate and livestock slurries) produced few measurable changes in soil properties in the short-term. However, over the long-term (i.e. up to 20 years), repeated livestock slurry additions to arable soils increased SOM and soil biological and physical functioning, although not to the same level as comparable applications of FYM. It is therefore possible that repeated digestate applications over a similar timeframe could lead to similar improvements. Indeed, although the long-term impact of digestates on soil properties is a largely unexplored field of research, Nkoa (2014) reviewed evidence from a number of studies which suggested that in the majority of cases, the short-term effects of digestate application resulted in an improvement in soil quality (microbial biomass, N and P contents), with one study reporting a reduction in bulk density and increase in soil moisture retention (Garg *et al*. 2005).

4.1.1 Soil organic matter

Soil organic matter (SOM) plays a central role in soil quality and functioning by providing a food source and habitat for the soil biological community thereby driving nutrient cycling. It is also a central component of soil aggregation and the maintenance of soil structure and water relations. Indeed, loss of SOM (due to changes in management, land-use and climate) is seen as one of the most important threats facing UK soils (Defra, 2009; Dobbie *et al*., 2011). The impact of management changes on SOM levels are often difficult to measure due to the large background soil concentrations and timescales involved, with changes after 3 years of repeated addition difficult to detect. The light organic matter fraction (LFOM) is a transitional pool of OM within soils between fresh residues and humified stable organic matter, largely comprising recent root and crop residue returns as well as partially decomposed organic matter from organic material additions (Gregorich *et al.,* 1997), and is considered to be a more labile source of soil carbon (Loveland *et al.,* 2001). As such, it has been shown to be more responsive to changes in land management or environmental conditions, acting as an 'early indicator' of the direction of change of the total SOM pool (Mahli *et al.,* 2003; Bhogal *et al*., 2011). The results from *DC-Agri* are in agreement with this, with the changes in LFOM greater than those measured in the total SOM pool. LFOM increased following the addition of bulky organic materials (compost and FYM), but changed very little following the addition of liquid organic materials (digestate and livestock slurry).

Comparable increases in SOM were observed for both 9 years of green compost addition and 20 years of FYM addition. The capacity of a soil to hold OM is finite such that after a change in management practice SOM will increase (e.g. after the introduction of regular organic material additions) or decrease (e.g after ploughing out long-term grass) towards an equilibrium (after 100 years or more) that is characteristic of the soil type, land use and climate (Powlson *et al*., 2012). Annual rates of SOM accumulation (or depletion) therefore change over time and gradually decline as the new equilibrium is approached, when they become zero. Typically, *c.*50% of the SOM accumulation achieved after 100 years of introducing a management change, occurs within the first 20 years (Powlson *et al*., 2012). It is possible that the rate of SOM accumulation on the long-term FYM treatment at Harper Adams and Terrington was entering this slower phase of accumulation. However, the retention of OM supplied by the green compost was almost double that of the FYM, suggesting that the OM in green compost was in a more stable form. The higher lignin content of the green compost (at *c.*70%) compared to the FYM (at *c.*55%) supports this conclusion. Moreover, characterisation of the organic material additions according to their carbon composition undertaken in a previous phase of experimentation at these sites (Defra Project SP530: SOIL-*QC*; Bhogal *et al*., 2009 & 2011), provides further evidence; here the total organic carbon (OC), lignin, cellulose and dissolved organic carbon (DOC) content of FYM and green compost were measured over a five year period, with the lignin fraction considered to be stable and more resistant to decomposition than the cellulose and DOC fractions. The SOIL-*QC* project found much greater differentiation between the stability of the applied materials compared to the 3 years of *DC-Agri* measurements, with almost 80% of the total OC within green compost in the form of lignin (stable), compared to just 30% for FYM. The greater stability of the OM supplied by the green compost additions therefore enabled a more rapid build-up of SOM over a shorter timeframe.

Retention of OM from the FYM was *c.*12%, which is identical to that reported by Maillard & Angers (2014) in a global meta-analysis of long-term field experiments with animal manures. Retention of compost OM was almost double that of FYM (20-25%), although not as great as that reported by Bhogal *et al.,* (2010) from four UK studies where green compost had been applied for 5-8 years (Wallace, 2005 & 2007) and OM retention was over 40% (± 8%). Given the interest in exploring potential land management strategies for increasing soil carbon storage in the mitigation of climate change, these OM retention coefficients are useful for improving national GHG inventory methodologies (Malliard & Angers, 2014) and demonstrate the value of green compost for increasing soil carbon storage.

4.1.2 Soil biological functioning

The soil microbial biomass mainly consists of bacteria and fungi which are a fundamental component of soils involved in nutrient cycling and release, as well as the development of soil structure through the production of organic 'glues' and fungal hyphae (Tisdall & Oades, 1982). Measurements of the size of the microbial pool (as determined by its C and N content) therefore gives an indication of a soil's ability to store and recycle nutrients, with higher contents generally linked to 'better' soil quality (Dick, 1992). Statistically significant increases in soil microbial biomass were found where green compost (and FYM and livestock slurry) had been applied for 9 or more years. The increases were greatest on the long-term FYM treatment, despite similar increases in SOM on the green compost treatment, most likely because the FYM applications comprised a more readily decomposable source of OM that was able to support a larger microbial population than that produced by the green compost additions.

Earthworms have a major influence on soil quality and are “probably, the most important soil macro-animal” (Brady, 1974). They are often referred to as “ecosystem engineers”, due to their role in breaking down organic matter, improving soil structure and allowing water/oxygen to move through the soil profile (Blouin *et al.*, 2013). Higher additions of fresh organic matter to soil are usually associated with greater earthworm populations, because of an abundance of food (Van Vliet *et al.*, 2007). Indeed, earthworm populations were greater following the application of FYM and to a lesser extent green and green/food compost to both arable and grassland soils, most likely due to the additional food supply provided by the organic materials. However, in some instances earthworm populations were lower following the application of food-based digestate, compared to the other treatments, including the fertiliser control. This was most clear at the Ayr grassland site, with effects still apparent *c.*2 years after the final digestate application (largely due to a reduction in the juvenile population). Earthworm numbers on the food-based digestate treatments at the grassland sites were most likely lower than on the other treatments because these sites had the largest earthworm populations, with the majority of the earthworms residing in close proximity to the soil surface (i.e. close to their main food-source) where the direct exposure to the digestate would be greater.

The laboratory experiments (Appendix 5) considered a number of different factors that were identified in the literature (Appendix 4) as having the potential to negatively affect earthworms. The results from the organic material analysis, contact tests and pot studies suggested conductivity, BOD and VFAs were not responsible for the lower numbers of earthworms observed in the field following the application of food-based digestate. But, ammonium-N was found to have a significant effect on earthworm survival and health, with ammonium-N loading (a function of both the ammonium-N concentration and application rate) most strongly explaining the negative effects observed. This conclusion is also consistent with the results of the original field experiments, where ammonium loadings were highest from the food-based digestate applications. Moreover the ammonium-N loading rate from food-based digestate at Ayr, where earthworm numbers were significantly lower than the fertiliser control, was amongst the highest applied at any site.

The laboratory experiments were important and valuable in understanding the causal factors and the effects of food-based digestate on earthworms. However, due to the worst-case nature of the pot studies (and particularly contact tests) and the fact they do not accurately simulate conditions in the field, it was not possible to derive a maximum ammonium-N loading.

4.1.3 Soil physical functioning

Topsoil bulk density has a direct impact on a number of essential soil physical and biological processes including gas exchange, root penetration, infiltration rates and soil faunal activity, and is usually a key measure in the assessment of soil quality as an indicator of soil compaction (Merrington *et al.,* 2006; Rickson *et al.,* 2012). Bulk density tends to be inversely related to SOM (Newell Price *et al.,* 2012), such that Merrington *et al.*, (2006) proposed higher ‘trigger values’ (i.e. the bulk density above which soil functions may be impaired) for soils with a lower SOM content. Moreover, decreases in bulk density associated with organic material additions (and higher SOM contents) have been shown to lead to a lower specific draught force for tillage and consequently lower fuel costs (Peltre *et al.,* 2015). At the arable sites, improvements in SOM and soil biological functioning on the long-term green compost (and FYM treatment) were associated with a decrease in bulk density. These decreases were again greater on the FYM treatment, despite similar SOM contents, which is similar to the pattern observed in the soil microbial pool, and demonstrates an important link between soil biological and physical functioning, particularly the role of the microbial community in the development of soil structure. However the time-frame over which this was achieved and the total OM load required to achieve it was almost double that of the green compost treatment. Another 4-6 years of experimentation would be required in order to establish whether a similar green compost OM loading could achieve the same level of improvement in soil biological and physical functioning as achieved on the long-term FYM treatment.

At the grassland sites, compost and FYM additions also decreased bulk density, but there was evidence of soil compaction (i.e. increased bulk density) where digestate and livestock slurry had been applied for 3 years. Soil compaction is often observed where livestock slurries have been applied due to heavy trafficking by the tanker during application, particularly if conducted under wet conditions. However on almost all occasions, all organic materials (including the livestock slurries and digestates) were applied by hand at the *DC-Agri* soil quality sites, so it is unlikely that soil compaction occurred as a result of the application method. It is possible that the volume, viscosity and conductivity of the liquids applied may have caused partial break-down (slaking) of the surface soil aggregates, leading to a decrease in porosity and increase in bulk density. However, this has not been widely reported as a problem with slurry applications to grassland and further experimentation would be required in order to elucidate the reasons behind the observed increases in bulk density.

4.1.4 Soil heavy metals and organic compound contaminants

There was virtually no effect of the compost and digestate additions on topsoil metal contents. Extractable Cu concentrations were increased (by *c.*1-2 mg/l) following addition of all the organic materials to the sandy soil at Harper Adams, and by the addition of green compost to the grassland soil at Lampeter. These increases in extractable Cu are not considered to be detrimental, indeed on certain soil types (e.g. peats and leached sandy soils) where Cu deficiency in cereal crops can occur, such additions may be beneficial (MAFF, 1984). Total and extractable Cu concentrations were also increased at the Terrington site, where the pig manures (both FYM and slurry) had been applied, reflecting high Cu concentrations in pig manures due to veterinary use and dietary supplementation with Cu (Nicholson *et al.*, 1999). However, increases in total Cu concentrations were small (only 2-5 mg/kg above the untreated control at 13 mg/kg) and well below maximum permissible concentrations in soils after sewage sludge application (i.e. 135 mg/kg/Cu at pH 6.0-7.0; Anon., 2009).

Likewise the concentrations of most of the measured OCCs were not affected by the compost and digestate additions, with the concentration of PAHs, dioxins and furans, and phthalates low or at the limits of analytical detection. PCB concentrations were marginally elevated where compost (both green and green/food) had been applied at three of the sites, but concentrations were still low at 5-10 x 10^{-4} mg/kg. In the UK, there are no specified 'safe' limits for OC concentrations in agricultural soils (or soil amendments such as sewage sludge, compost and digestate). However, a set of preliminary, human health related numerical limits for OCCs in soil was developed by Chang *et al.* (2002) for land application of wastewater and sewage sludge. For PCBs, Chang *et al.* (2002) proposed a guideline maximum permitted soil concentration of 0.89 mg/kg. The concentrations measured at the *DC-Agri* experimental sites (at <0.002 mg/kg) were therefore well below this concentration. These results are in line with those of Suominem *et al.* (2014) who quantified the potential loading of OCCs from the application of a range of digestates (including food and manure-based as well as those derived from the digestion of municipal wastes and biosolids) to arable soils in Finland and observed that the annual loadings of dioxins, furans, phthalates and PCBs were similar to or lower than those from atmospheric deposition in Scandinavia and were therefore of low-risk to food safety. This is an important finding for the sustainable use of these materials on agricultural land used for food production, providing confidence that the quality of agricultural soils will not be impaired by a build-up of potentially harmful heavy metals and OCCs.

4.2 Crop quality

The aim of each site's nutrient management plan was to ensure (as far as practically possible) that no major nutrient limited crop growth and that crop yields and residue returns were the same on all treatments (so that the only difference in organic carbon inputs would be from the applied organic materials). Manufactured fertiliser N was therefore applied each year at variable rates after accounting for the crop available N supplied by the organic materials. Manufactured fertiliser P, K and S was applied at a single rate across all treatments, based on the requirements of the untreated control (these were largely 'maintenance' dressings applied at rates to replace crop offtake; Defra, 2010b; SAC, 2010). This meant that the supply of P, K, S from the organic materials (Table 6) was in addition to the manufactured fertiliser additions. This not only led to a build-up of these nutrients in the topsoil (Table 10) but was most likely responsible for the measured yield increases in the majority of site/seasons (Table 11), with little evidence of a longer-term organic matter benefit on crop yields. The results therefore provide a clear demonstration of the value of an integrated nutrient management plan, using both compost/digestate and manufactured fertiliser, with the organic materials providing additional nutrients (i.e. a '*nutrient boost*') early in the season thereby resulting in increased crop yields. This is particularly important on P-fixing soils (e.g. shallow soils over chalk such as Devizes), soils with a low nutrient status (e.g. Lampeter) or susceptible to S deficiency (e.g. sandy soils where S deposition is low, such as at Aberdeen). Indeed, the measured yield increases at Devizes as a result of the additional P supply, particularly from the compost applications, were worth between £100-160/ha, taking into account the value of fertiliser saved and cost of spreading (but not sourcing) the compost (Table 13). This was similar to the benefit obtained from applying FYM, with livestock slurry providing greater benefits (£210/ha) due to the additional N supply, whereas food-based digestate, having a lower P content, gave a benefit of £55/ha (Table 13).

Table 13 Cost-benefit analysis for organic material use at Devizes, based on results from harvest 2012.

	Green compost (25 t/ha)	**Green/food compost (20 t/ha)**	**Food-based digestate (41 m^3/ha)**	**Farmyard manure (35 t/ha)**	**Cattle slurry (80 m^3/ha)**
Value (£/ha) of yield increase[1]	+120	+140	+80	+120	+270
Value (£/ha) of manufactured fertiliser N saving[2]	~	+10	+70	+20	+110
P_20_5 savings (£/ha)[2]	+60	+76	+16	+90	+58
Organic material spreading cost (£/ha)[3]	-75	-60	-123	-70	-240
Saved spreading cost of N fertiliser (£/ha)[4]	~	~	+12	~	+12
Net benefit (£/ha)	105	166	55	160	210
COST-BENEFIT RATIO	1:2.4	1:3.8	1:1.4	1:3.3	1:1.9

[1] Grain valued at £190/tonne
[2] N fertiliser = 90 p/kg; P_20_5 = 80 p/kg
[3] Spreading costs on farm: Solid materials £3/tonne: Band spread liquid materials £3/m^3
[4] Cost of spreading N fertiliser: £12/ha
~ Negligible
Note: No allowance made for K, S and Mg supplied by organic materials as soil status satisfactory; or for longer-term organic matter benefits. Costs of sourcing the organic materials are not included

The repeated organic material additions had no detrimental effect on the quality of the harvested products as measured by the specific weight, protein and mycotoxin content of cereal grain at Devizes and Harper Adams, the oil content of rape seed at Aberdeen and Terrington and the total metal content of all harvested materials at each site. The 'nutrient boost' provided by the organic material additions resulted in higher specific grain weights at Devizes – a key property for milling wheat, and there was no detrimental effect of the organic material additions on the presence of mycotoxins (DON & ZON) or metal concentrations. DON and ZON are frequently detected in wheat, but average concentrations are usually below the legal limits. Indeed, across the UK during the period 2001 to 2013 it was only in wet harvest years (2008) that a significant percentage exceeded the legal limits for DON and ZON (HGCA, 2014b). There was also no evidence of soil/organic material contamination of the cut grass at Lampeter and Ayr. Mo concentrations were elevated in the grass grown at Lampeter following FYM applications and at Ayr following compost addition, but not at levels considered to be problematic for the uptake of Cu by grazing animals.

5.0 WP1 Conclusions

The overall aim of this work package was to evaluate the effects of repeated compost and digestate applications on soil and crop quality, with livestock manures and slurries included within the experimental design as comparator materials and a fertiliser control. The results have clearly demonstrated that the repeated application of compost is a valuable means by which farmers can improve soil organic matter status, with associated increases in soil biological and physical functioning. This will ultimately lead to increases in crop yield and resilience (due to improved rooting, nutrient and water acquisition), particularly in poor growing seasons (e.g. where low rainfall induces water stress, or high rainfall prevents vehicular access and delays fertiliser application). Higher crop yields, with less reliance on manufactured fertiliser inputs and reduced energy costs (through easier cultivation and hence fuel consumption) can also lead to improved financial returns. This conclusion was based largely on changes in soil properties achieved after the long-term (9 years) application of green compost, although the direction of change in soil properties following 3 years of green and green/food compost was the same. Repeated digestate applications (both food and manure-based) had limited capacity to improve soil biological and physical functioning, due to the low organic matter loading associated with these materials, but did improve the soil nutrient status, with all organic materials providing a 'nutrient boost' leading to higher crop yields. The absence of any effects on the total soil metal and OCC content and crop metal contents was also an important finding for the sustainable use of these materials in food production. However, food-based digestate applications did have an impact on earthworm populations at the grassland sites, with both livestock slurry and digestate applications causing an increase in compaction at these sites (bulk density, shear strength and penetration resistance). The key findings are summarised below:

Effect of quality compost (PAS100) additions on soil and crop quality:

- Green and green/food compost additions improved soil nutrient status (N, P, K, Mg, S) within a short timescale (< 3 years), but other properties, such as total SOM, microbial biomass and selected soil physical properties only changed in a quantifiable way after multiple applications (9 years) of green compost.
- Long-term additions of green compost (9 years) improved soil biological and physical functioning, increasing the ability of soils to provide crop-available N and improving soil structure and workability. This has the potential to enable greater root exploration (and consequently crop nutrient and water acquisition), reduce the risk of soil erosion and make cultivations easier (reducing fuel consumption).
- Compost is a good source of stable OM which is relatively resistant to decomposition and consequently leads to a more rapid build-up of SOM compared to FYM.
- Compost additions resulted in higher earthworm numbers.
- Compost additions had no impact on soil heavy metal or organic contaminant compound concentrations or negative effects on the quality of crops grown.
- Compost provided a 'nutrient boost' early in the season thereby resulting in increased crop yields, with a cost:benefit ratio ranging between 1:2.4 and 1:3.8.

Effect of digestate additions on soil and crop quality:

- Digestate was a good source of plant nutrients and led to an increase in soil nutrient status within a short (<3 yrs) time period. However, as it had a low dry matter content, it was not very effective at improving soil biological and physical functioning, due to the small quantity of organic matter applied.

- There were no detrimental effects of digestate additions on soil heavy metal or organic contaminant compound concentrations, and crop quality.
- Digestate provided a 'nutrient boost' early in the season thereby resulting in increased crop yields, with a cost:benefit ratio of 1:1.4.
- Food-based digestate was sometimes associated with lower earthworm numbers compared to other treatments, particularly at the grassland sites where digestate treatment showed lower numbers than fertiliser controls. Laboratory studies concluded that ammonium-N loading (a function of both the NH_4-N concentration and application rate) most strongly explained the negative effects observed. This is consistent with the results of the field experiments, where ammonium-N loadings were highest from the food-based digestate. Due to the worst-case nature of the pot studies (and particularly contact tests) and the fact they do not accurately simulate conditions in the field, it was not possible to derive a maximum ammonium-N loading.

6.0 References

Anon, (2009) *Protecting our Water, Soil and Air – A Code of Good Agricultural Practice for Farmers, Growers and Land Managers.* Crown Publications, London.

Bhogal, A., Nicholson, F.A., Chambers, B.J. (2009) Organic carbon additions: effects on soil bio-physical and physico-chemical properties. *European Journal of Soil Science* **60**, 276–286.

Bhogal, A., Chambers, B.J. Whitmore, A.P. & Powlson, D.S. (2010) *Effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Final report to Defra for project SP0561.

Bhogal A., Nicholson F.A., Young, I, Sturrock C., Whitmore A.P. & Chambers B.J. (2011) Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality. *European Journal of Soil Science* **62**, 174-181.

Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Dai, J., Dendooven, L., Peres, G., Tondoh, J.E., Cluzeau, D. & Brun, J.J. (2013) A review of earthworm impact on soil function and ecosystems services. *European Journal of Soil Science*, **64**, 161-182.

Brady, N.C. (1974) *The Nature and Properties of Soils* (8th Edition). Macmillan Publishing Co., Inc.

Brookes, P.C., Landman, A., Pruden, G. & Jenkinson, D.S. (1985) Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry* **17**, 837-842.

Burnham, K.P. & Anderson, D.R. (2002) *Model selection and multi-model inference: a practical information-theoretic approach.* 2nd Edition, Springer, New York.

Chang A. C., Pan, G., Page, A.L. & Takashi Asano, T. (2002) *Developing Human Health-related Chemical Guidelines for Reclaimed Water and Sewage Sludge Applications in Agriculture.* Prepared for World Health Organization. http://www.who.int/water_sanitation _health/wastewater/gwwuchemicals.pdf

Clements, L.J., Salter, A.M., Banks, C.J. & Poppy, G.M. (2012) The usability of digestate in organic farming. *Water Science and Technology* **66**, 1864-1870.

Defra (2009) *Safeguarding our Soils: A Strategy for England*. Crown Publications. http://defraweb/environment/land/soil/index.htm

Defra (2010a) *HM Government Food 2030*. http://www.defra.gov.uk/foodfarm/food/strategy

Defra (2010b) *The Fertiliser Manual (RB209).* The Stationary Office, Norwich

Dick, R.P. (1992) A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. *Agriculture, Ecosystems and Environment*, **40**, 25-36.

Dobbie KE, Bruneau PMC & Towers W (eds) (2011) *The State of Scotland's Soil*. Natural Scotland. www.sepa.org.uk/land/land_publications.aspx

Edmeades, D.C. (2003) The long-term effects of manures and fertilisers on soil productivity and quality: a review. *Nutrient Cycling in Agroecosystems*, **66**, 165-180.

Garg, R. N, Pathak, H., Das, D.K. & Tomar, R.K. (2005) Use of flyash and biogas slurry for improving wheat yield and physical properties of soil. *Environmental Monitoring and Assessment*, **107**, 1-9.

Gregorich, E.G., Drury, C.F., Ellert, B.H. & Liang, B.C. (1997) Fertilisation effects on physically protected light fraction organic matter. *Soil Science Society of America Journal*, **61**, 482-484.

Haynes, R.J. & Naidu, R. (1998) Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems*, **51**, 123-137.

HGCA (2009) *Nitrogen for winter wheat – management guidelines*. www.HGCA.com

HGCA (2013) *AHDB/HGCA 2013 Cereal Quality Survey Results*. www.HGCA.com

HGCA (2014a) *Sulphur for cereals and oilseed rape*. Information Sheet 28, spring 2014. www.HGCA.com

HGCA (2014b) *Guidelines to minimised risk of Fusarium mycotoxins in cereals*. www.HGCA.com

ISO (2009) *Soil quality – Sampling – Part 6; Guidance on the collection, handling and storage of soil under aerobic conditions for the assessment of microbiological processes, biomass and diversity in the laboratory*. International Standard. ISO 10381-6:2009 E.

Keeney, D.R. (1982) Nitrogen availability indices. In: *Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties* (Eds. A.L. Page, R.H. Miller & D.R. Keeney), American Society of Agronomy, Madison, USA. pp. 199-244.

Johnston, A.E., Poulton, P.R. & Coleman, K. (2009) Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy*, **101**, 1-57.

Loveland, P.J., Webb, J. & Bellamy, P. (2001) Critical levels of soil organic matter: the evidence for England and Wales. In: Sustainable *Management of Soil Organic Matter* (Eds. R.M. Rees, B.C. Ball, C.D. Campbell & C.A. Watson), CAB International, Wallingford, Oxford, pp. 23-33.

MAFF, (1983) *Trace Element Deficiencies in Field Crops*. MAFF Reference Booklet 2197, HMSO.

MAFF, (1986) *The Analysis of Agricultural Materials*. MAFF Reference Book 427. London. HMSO.

Maillard, E. & Angers, D.A. (2014) Animal manure application and soil organic carbon stocks: a meta-analysis. *Global Change Biology*, **20**, 666-679

Malhi, S.S., Harapiak, J.T., Nyborg, M., Gill, K.S., Monreal, C.M. & Gregorich, E.G. (2003) Total and light fraction organic C in a thin Black Chernozemic grassland soil as affected by 27 annual applications of six rates of fertilizer N. *Nutrient Cycling in Agroecosystems*, **66**, 33-41

Merrington G, Fishwick S, Barraclough D, Morris J, Preedy N, Boucard T, Reeve M, Smith P & Fang C (2006) The development and use of soil quality indicators for assessing the role of soil in environmental interactions. Environment Agency Science Report SC030265, Bristol, UK

Nicholson, F.A., Chambers, B.J., Williams, J.R. & Unwin, R.J. (1999) Heavy metal contents of livestock feeds and animal manures in England and Wales. *Bioresource Technology*, **70**, 23 –31

Nicholson F A, Bhogal A, Chadwick D, Gill E, Gooday R D, Lord E, Misselbrook T, Rollet A J, Sagoo L, Smith K A, Thorman R E, Williams J R, & Chambers B J. (2013) An enhanced software tool to support better use of manure nutrients: MANNER-*NPK*. *Soil Use and Management*, **29,** 473-484.

Newell-Price, P., Chambers, B.J. & Whittingham, M.J. (2012) *Characterisation of Soil Structural Degradation Under Grassland and Development of Measures to Ameliorate its Impact on Biodiversity and other Soil Functions*. Report to Defra for BD5001:WP1 Characterisation of soil compaction under grassland.

Nkoa, R. (2014) Agricultural benefits and environmental risks of soil fertilisation with anaerobic digestates: a review. *Agronomy for Sustainable Development*, **34**, 473-492.

Pelosi, C., Chiron, F., Dubs, F., Medde, M., Ponge, J.F., Salmon, S., Cluzeau, D. & Nelieu, S. (2014) A new method to measure allyl isothiocyanate (AITC) concentrations in mustard – Comparisons of AITC and commercial mustard solutions as worm extractants. *Applied Soil Ecology*, **80**, 1-5.

Peltre, C., Nyord, T., Bruun, S., Jensen, L.S. & Magid, J. (2015) Repeated soil application of organic waste amendments reduces draught force and fuel consumption for soil tillage. *Agriculture, Ecosystems & Environment*, **211**, 94-101.

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T. & Whitmore, A.P. (2012) The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agriculture Ecosystems & Environment*, **146**, 23-33.

Richards, S.A. (2005) Testing ecological theory using the information-theoretic approach : examples and cautionary results. *Ecology*, **86**, 2805-2814.

Richards, S.A. (2008) Dealing with overdispersed count data in applied ecology. *Journal of Applied Ecology*, **45**, 218-227.

Richards, S., Whittingham, M.J. & Stephens, P.A. (2011) Model selection and model averaging in behavioural ecology: the utility of the IT-AIC framework. *Behaviour, Ecology & Sociobiology*, **65**, 77-89.

Rogers, P., Gatelly, T. & Keating, T. (2000) *Teagasc Farm Nutrient Profile*. http://homepage.eircom.net/~progers/2manual.htm#soimol Accessed 29/4/15.

Rickson, R.J., Deeks, L.K., Corstanje, R., Newell-Price, P., Kibblewhite, M.G., Chambers, B., Bellamy, P., Holman, I., James, I.T., Jones, R., Kechavarsi, C., Mouazen, A.M., Ritz, K. & Waine, T. (2012) *Soil Quality Indicators - Physical Properties*. Final Report to Defra for project SP1611.

SAC (2010) *Phosphorus, potassium, sulphur and magnesium recommendations for cereals, oilseed rape and potatoes.* Technical Note TN633, SAC August 2010.

Schmidt, O. (2001) Time-limited soil sorting for long-term monitoring of earthworm populations. *Pedobiologia*, **45**, 69-83.

Scullion, J., Smith, A.R., Gwyn-Jones, D., Jones, D.L. & Goodbold, D.L. (2014) Deciduous woodland exposure to elevated atmospheric CO_2 had species-specific impacts on anecic earthworms. *Applied Soil Ecology*, **80**, 84-92.

Suominen, K., Verta, M. & Marttinene, S. (2014) Hazardous organic compounds in biogas plant end products – soil burden and risk to food safety. *Science of the Total Environment* **491-492**: 192-199.

Tisdall, J.M. & Oades, J.M. (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, **33,** 141-163.

Van Vliet, P.C.J., Can der Stelt, B., Rietberg, P.I. & De Goede, R.G.M. (2007) Effects of organic matter content on earthworms and nitrogen mineralization in grassland soils. *European Journal of Soil Biology*, **43**, S222-S229.

Verzani, J. (2014) Using R for Introductory Statistics. CRC/Chapman and Hall Press.

Wallace, P. (2005) Compost Use in Agriculture. Consolidated report, 2005. www.compost.me.uk

Wallace, P. (2007) Compost Use in Agriculture. Consolidated report phase 2, 2007. www.Compost.me.uk

Whittingham, M.J., Swetnam, R.D., Wilson, J.D., Chamberlain, D.E. & Freckleton, R.P. (2005) Habitat selection by yellowhammers *Emberiza citrinella* on lowland farmland at two spatial scales: implications for conservation management. *Journal of Applied Ecology*, **42**, 270-280.

Whittingham, M.J., Stephens, P. Bradbury, R.B. & Freckleton, R.P. (2006) Why do we still use stepwise modelling in ecology and behaviour? *Journal of Animal Ecology*, **75**, 1182-1189.

WRAP (2013) A Survey of the UK Organics Recycling Industry in 2012. Waste and Resources Action Programme 2013.

WRAP (2014) A Survey of the UK Anaerobic Digestion Industry in 2013. Waste and Resources Action Programme 2014.

Wu, J., Joergensen, R.G., Pommerening, B., Chaussod, R. & Brookes, P.C. (1990) Measurement of soil microbial biomass C by fumigation-extraction – an automated procedure. *Soil Biology and Biochemistry*, **22**, 1167-1169.

www.wrap.org.uk/dc-agri