TECHNICAL ARTICLE

Long-term Effects of Biosolids on Soil Quality and Fertility

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ABSTRACT:
Biosolids are an important potential source of plant-available nutrients and also contain valuable quantities of stable organic matter, which can provide long-term benefits to soil structure and fertility. In this study, the long-term impacts of biosolids recycling to agricultural land on soil quality and fertility were assessed using established experimental platforms at four sites in England with contrasting soil types and agroclimatic conditions. At each site, treatment plots that had received 20 annual additions of biosolids (i.e., three types of digested sludge cake) at rates of 2.9 to 3.4 t ha^{-1} y^{-1} since 1994 were used in comparison with an untreated control treatment (which had received inorganic fertilizers only) to quantify the effects of biosolids on soil physical, chemical, and biological properties. Significant increases ($P < 0.05$) in soil organic matter (SOM) of 10% to 17% and in "light fraction" SOM (up to 2.9 mg kg^{-1} on the biosolids treatment compared with 1.8 mg kg^{-1} on the untreated control), along with a significant ($P < 0.01$) increase of up to 10% in available water capacity and numerical increases in water infiltration rate and aggregate stability, were found in plots that received biosolids. These plots also had significant ($P < 0.05$) increases of up to 20%, 48%, and 30% in soil total nitrogen, extractable phosphorus, and total sulfur, respectively. Earthworm numbers and weights were approximately doubled relative to the untreated control ($P < 0.05$) where low-metal biosolids had been applied. These results indicate that applying biosolids to agricultural land is an important means of replenishing and maintaining SOM levels. Importantly, no adverse effects on crop quality were observed. The results from this study provided valuable evidence toward maintaining a sustainable agricultural landbank for biosolids recycling in the United Kingdom.

Key Words: Arenosol, Rendzina, Cambisol, Luvisol, treated sewage sludge, winter wheat

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Biosolids (treated sewage sludge) are an important source of crop-available nitrogen (N) and phosphorus (P), as well as other major and minor plant nutrients, and as a result of some conditioning processes can have value as a liming material. They also contain valuable quantities of stable organic matter (OM) and are therefore an important means of replenishing or maintaining soil organic matter (SOM) levels, which are closely linked to soil properties that have an important influence on soil quality and fertility and hence on sustainable crop production.

Extensive research effort has been devoted to concerns related to the long-term effects of biosolids recycling to agricultural land including increased soil heavy metal concentrations and the implications for soil quality (see, e.g., Charlton et al., 2016). Recent studies have investigated "emerging" organic chemicals that may have adverse effects on human health or the environment (Clarke and Smith 2011), and other potentially harmful contaminants such as microplastics and synthetic fibers (e.g., see Zubris and Richards, 2005) and nanoparticles (e.g., see Durenkamp et al., 2016). However, it is important to balance these potential issues against the benefits provided by biosolids additions, which have been demonstrated to be a valuable source of both immediately crop-available and slow-release nutrients (e.g., see Rigby et al., 2009; Rouch et al., 2011; Lu et al., 2012; Withers et al., 2016; Rigby et al., 2016). This is indeed one of the main reasons that many farmers are keen to apply biosolids. Various authors have studied the improvements in soil physical properties resulting from biosolids additions as reviewed by Lu et al. (2012), as well as assessing how biosolids recycling might contribute to increases in soil organic carbon stocks and hence contribute to climate change mitigation (Powlson et al., 2012). However, most of these studies tend to be relatively short term (<10 years) and in general have focused on a small number of selected soil chemical, biological, or physical properties rather than taking a more holistic approach to the overall impact of the applied biosolids.

Application to agricultural land is still seen as the best practical environmental option for recycling biosolids in the United Kingdom. It is therefore not surprising that 77% of the 1.4 million tonnes (dry solids) of biosolids currently produced in the United Kingdom each year are recycled to agricultural land (Water UK 2010). At an average application rate of 6.5 t ha^{-1} dry solids, this equates to approximately 170,000 ha of agricultural land receiving biosolids annually. In our previous study, which assessed the effects of 5 years of repeated biosolids additions, Chambers et al. (2003) reported changes in some soil biophysical and physicochemical properties (e.g., plant-available water capacity [AWC]), but not others (e.g., soil microbial activity, structural stability, soil strength). The lack of measured effects was no doubt due (in part) to the relatively low amounts of OM applied by the biosolids (OM loading rates in the range of approximately 5–9 t ha^{-1}) at the sites. Therefore, in this study, we used experimental plots that had received 20 years of biosolids additions (Gibbs et al., 2006) to better assess the effects of repeated biosolids OM additions on soil biophysical and physicochemical properties, as they had received much greater OM loadings (approximately 12–33 t ha^{-1}).

MATERIALS AND METHODS

Sites and Treatments

The sites and treatments had previously been established as part of a long-term project designed to test the effects on soil fertility and microbial activity of heavy metals applied to agricultural land with biosolids (see Chaudri et al., 2008; Gibbs et al., 2006). Established experimental platforms at four sites in England with contrasting soil types and agroclimatic conditions were utilized (Table 1). At each site, treatment plots that had received repeated annual biosolids (digested cake) additions since 1994 were used in comparison with an untreated control treatment (which had received inorganic fertilizers only) to quantify the effects of the biosolids

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TABLE 1. Site and Treatment Details

Sites	Average Annual Rainfall (mm)	Average Temperature (°C)	FAO* Soil Class	Topsoil Texture	Sand (>63 μm) (%)	Silt (2–63 μm) (%)	Clay (<2 μm) (%)	Organic Carbon (%)	pH	Rotation	Crop Grown in 2014
1. Bridgets/Hampshire	758	11.0	Rendzina	Silty clay loam	10 (0.9)	60 (2.9)	30 (2.0)	1.5 (0.12)	6.8 (<0.01)	Ley/arable	Winter (milling) wheat
2. Gleadthorpe/ Nottinghamshire	650	9.8	Cambisol	Sandy loam	71 (1.7)	22 (1.5)	7 (0.3)	1.2 (0.06)	7.1 (0.06)	Ley/arable	Winter (malting) barley
3. Rosemaund/ Herefordshire	703	10.4	Luvisol	Silty clay loam	8 (0.7)	67 (0.7)	25 (0.7)	1.7 (0.12)	7.0 (0.09)	Arable	Winter wheat
4. Woburn/Bedfordshire	652	10.6	Arenosol	Loamy sand	80 (1.2)	12 (0.9)	8 (0.3)	1.3 (0.07)	7.2 (<0.01)	Arable	Winter wheat

Values in parentheses are standard errors (n = 3).
*FAO (1998).

additions on soil physical, chemical, and biological properties. Low-metal biosolids (BS1) were applied in comparison with biosolids that were rich in zinc (Zn) (BS2) or cadmium (Cd) and copper (Cu) (BS3) so that the effects of these metals applied (at maximum permitted rates) over a long time period could be ascertained. Present-day biosolids products have heavy metal profiles, which align to the low-metal BS1 treatment; it is very unlikely that biosolids with similar metal concentrations to the metal-rich (BS2 and BS3) treatments would be applied to agricultural land today.

At each site, three treatments that had received repeated biosolids (three types of digested sludge cake) additions for 20 years up to the end of 2013 (at a rate of approximately 3 tonnes dry solids [tds] ha^{-1} y^{-1}) were utilized for the soil quality measurements (Table 1). Each treatment was replicated three times to give a total of 12 plots, including the inorganic fertilizer-only control. Plots were bounded by permanent grass strips to prevent soil movement during cultivation. Cultivations were carried out annually using a spading machine (Celli SpA, Forli, Italy) to help ensure that the biosolids additions were evenly incorporated throughout the topsoil depth and to encourage breakdown of the OM in the biosolids (Gibbs et al., 2006).

Since the experiment started in 1994, all the treatments, including the control, had manufactured fertilizers (N, P, potassium [K], and sulfur [S]) applied at the same rate and did not account for nutrients supplied by the biosolids. Manufactured fertilizer additions depended on the crop being grown as part of the arable or ley/arable rotation at each site and were based on the requirements of the control (fertilizer only) treatment; thus, fertilizer applications varied between the sites and years. Lime was applied where necessary to ensure that the soil pH was maintained at the optimum level for the crop being grown (Defra 2010). This regime ensured that, as far as was practically possible, no major nutrient limited plant growth and that crop yields and residue returns over the whole 20-year experimental period were the same on all treatments at a particular site (i.e., the only difference in OM inputs was from the applied biosolids).

Cereal crops were grown at each site for harvest in 2014 (Table 1) using commercially recommended seed rates, with agrochemicals applied as needed and according to good agricultural practice to control weeds, pests, and diseases.

Sampling and Measurements

Topsoil samples were taken in April and May 1994 prior to the first sludge cake applications to characterize each site (Table 1; Gibbs et al., 2006) and again in spring 2014 (0- to 15-cm depth, Defra, 2010). Samples (approximately 5 kg per plot) were homogenized then divided and either air dried prior to soil chemical analysis or stored, field moist, at 4°C prior to determination of soil biological properties as described below:

Soil organic carbon was measured according to Walkley and Black (1934) and was converted to OM using a coefficient of 1.724. Loss on ignition (LOI) was used to determine the volatile solids (including OM) content. The "light fraction" of SOM (LFOM) was determined using the method of Gregorich and Eller (1993).

Total N was measured by Kjeldahl digestion, total S by combustion, cation exchange capacity (CEC) by extraction with ammonium acetate/K chloride, Olsen extractable P, ammonium nitrate extractable K, magnesium (Mg), and S and pH in water, all using standard methods (Anon 1986). Sequential P fractionation was performed using a modified version of the Hedley sequential fractionation technique (Hedley et al., 1982).

Prior to determination of soil biological properties, soils were preincubated for 7 days at 25°C and approximately 50% water content at field capacity (or 0.05 bars). Soil microbial biomass C and N contents were measured using the chloroform fumigation-extraction technique (Brookes et al., 1985; Vance et al., 1987; Wu et al., 1990). Dissolved organic C was measured in the K sulfate extract from the unfumigated soil samples (Wu et al., 1990) using a total organic carbon analyzer (TOC-VCPH) (Shimadzu UK Ltd, Milton Keynes, United Kingdom). Soil respiration was determined by measuring the amount of carbon dioxide evolving from a sample of soil under controlled conditions (Alef 1995) and potentially mineralizable N (PMN) by using an anaerobic incubation technique (Keeney 1982). Earthworm populations were measured by *in situ* application of "hot" mustard and recording the total number and weight of earthworms (adults and immature worms).

A range of soil physical properties were measured at each of the four sites during spring 2014. Plant-available water capacity was measured by calculating the volumetric moisture content of the soil between 0.05 and 15 bars (Anon 1982). Bulk density was determined using metal cylinders of known internal volume and determining the oven dry weight of the soil (Anon 1982); air capacity and porosity were calculated from the bulk density. Soil shear strength (0- to 7.5-cm depth) was determined *in situ* using a Pilcon hand vane (Impact Test Equipment, Stevenston, United Kingdom), and the maximum penetration resistance to a depth of 15 cm was measured using a cone penetrometer (Anon 1982); 10 replicate measurements were undertaken on each plot. Aggregate stability was measured using the dispersion ratio technique on 10- to 20-mm aggregates (Anon 1982). The initial and equilibrium (saturated) soil water infiltration rate was measured *in situ* on each plot using double-ring infiltrometers (Anon, 1982).

Measurements of crop yields and quality were made at harvest in 2014. Grain yields were measured using a small plot combine, and grain samples were analyzed for dry matter, specific weight, protein content, and total concentrations of N, P, K, S, Mg, Zn, Cu, Cd, lead, nickel, chromium, and mercury using standard methods (Anon., 1986). Grain samples were provided for milling and baking, and malting and brewing trials using the Triangle Test Method (BS EN ISO, 2007) for testing bread samples and standard industry methods (Analytica EBC; http://www.analytica-ebc.com) for testing beer samples.

Statistical analysis

Analysis of variance comparisons were undertaken on the data from each experimental site. Cross-site analyses of variance were performed on the pooled site data to assess whether a particular treatment had a statistically significant effect on soil properties across all four study sites. Duncan (1955) multiple-range test was used to determine whether differences between treatments were significant. All statistics were performed using GenStat version 12.2 (VSN International Ltd, Hemel Hempstead, United Kingdom).

RESULTS AND DISCUSSION

Organic Matter and Nutrient Additions With Biosolids

After 20 years of annual applications, the biosolids treatments had added between 12 and 33 t ha^{-1} of OM to the soil at each site (Table 2). Present-day digested cake applications are likely to supply somewhat higher rates of OM and nutrients per application (Table 2); therefore, in practice, it may take fewer than 20 annual applications to achieve the same total OM and nutrient loadings as in this study.

Increases in SOM

Soil OM is a key indicator of soil quality and fertility. Loss of SOM (due to changes in management, land use, and climate) is seen as one of the most important threats facing UK soils and a contributor to global warming (Defra 2009; Dobbie et al., 2011). However, the impact of management changes on SOM levels are often difficult to measure because of high background SOM concentrations and the long timescales involved.

There are various methods available for assessing OM including the Walkley and Black (1934) method, which is a wet oxidation technique to determine the organic carbon present in soil, and LOI, where the percentage weight loss of a soil sample is determined after ashing at a specified temperature to determine the SOM content. There were significant ($P < 0.01$) differences in SOM between the sites when measured by the Walkley-Black method, although there were no significant site × treatment interactions (Table 3). Biosolids applications increased SOM contents on all the biosolids treatments at Bridgets and Woburn compared with the inorganic fertilizer control, and on the BS1 and BS2 treatments at Rosemaund, although these differences could not be confirmed statistically ($P > 0.05$). Cross-site analysis showed that on average the BS2 treatment had higher SOM contents (3.1%) than the untreated control (2.8%; $P = 0.09$).

When SOM was measured using LOI, there were significant ($P < 0.05$) differences between the sites, and again no significant site × treatment interactions ($P > 0.05$). There was a significant increase ($P < 0.05$) in LOI of 10% and 17% on the BS1 and BS2 treatments, respectively, compared with the control treatment, but not on the BS3 treatment (Fig. 1), reflecting the different quantities of OM applied with these treatments (Table 2). Assuming the measurements of LOI were directly equivalent to SOM, these increases equated to an additional 12 and 20 t ha^{-1} SOM in the topsoil,

TABLE 2. Average Total Loadings of Biosolids Dry Solids, OM, and Nutrients Over the 20-Year Experimental Period (1994–2013) and Average Annual Addition Rates

Treatment*	Dry Solids	OM	N	P
Average total addition (t ha^{-1})				
BS1	57.5 (0.2)	32.8 (0.14)	3.0 (0.01)	1.2 (<0.01)
BS2	64.6 (1.7)	33.0 (0.86)	2.7 (0.07)	1.7 (0.04)
BS3	67.2 (0.4)	11.9 (0.07)	0.8 (<0.01)	1.1 (0.01)
Average annual rate of addition (t ha^{-1} y^{-1})				
BS1	2.9	1.6	0.15	0.06
BS2	3.2	1.6	0.13	0.08
BS3	3.4	0.6	0.04	0.06
Present-day biosolids†	*5.0*	*2.5*	*0.22*	*0.16*

Values in parentheses are standard errors (n = 4).

*Treatments were as follows: control—manufactured fertilizer only (no biosolids applied); BS1—biosolids digested cake (low metal content); BS2—biosolids digested cake (Zn-rich); BS3—biosolids digested cake (Cd-rich).

†Addition rates from a typical present-day digested cake application are shown as a comparison (Defra 2010). Assumes digested cake contains 50% OM.

TABLE 3. Soil OM, LFOM, CEC, AWC, Infiltration Rate, Aggregate Stability, Topsoil Total N, and Potentially Mineralizable N at Each Site in 2014

	Bridgets	Gleadthorpe	Rosemaund	Woburn	All sites
SOM (%)					
Control	3.14 (0.06)	3.03 (0.14)	3.36 (0.27)	1.74 (0.05)	2.81
BS1	3.24 (0.12)	2.65 (0.12)	3.40 (0.42)	2.10 (0.21)	2.84
BS2	3.69 (0.51)	3.02 (0.38)	3.55 (0.25)	2.24 (0.07)	3.12
BS3	3.41 (0.21)	2.72 (0.21)	3.09 (0.18)	2.09 (0.06)	2.83
P (site)					<0.01
P (treatment)	ns	ns	ns	ns (0.06)	ns (0.09)
P (site × treatment)					ns
Light fraction OM (g kg^{-1})					
Control	1.23^a (0.10)	1.98 (0.18)	0.94 (0.20)	2.92 (0.55)	1.77^a
BS1	1.06^a (0.16)	2.04 (0.55)	0.97 (0.09)	2.41 (0.49)	1.62^a
BS2	2.18^b (0.21)	2.99 (0.47)	2.69 (1.03)	3.69 (0.22)	2.88^b
BS3	1.09^a (0.18)	1.86 (0.53)	0.97 (0.01)	3.14 (0.40)	1.77^a
P (site)					<0.001
P (treatment)	<0.05	ns	ns	ns	<0.001
P (site × treatment)					ns
CEC (mEq 100 g^{-1})					
Control	12.7 (0.8)	6.3 (0.6)	11.7 (0.3)	5.1 (0.4)	8.9^a
BS1	14.2 (0.2)	6.3 (0.3)	12.7 (0.4)	6.1 (0.5)	9.8^b
BS2	15.1 (0.9)	6.1 (0.9)	13.2 (0.5)	5.7 (0.4)	10.0^b
BS3	14.0 (0.6)	5.8 (0.3)	12.8 (0.3)	5.6 (0.5)	9.6^{ab}
P (site)					<0.001
P (treatment)	ns (0.09)	ns	ns	ns	<0.05
P (site × treatment)					ns
AWC (%)					
Control	28.7^c (1.3)	23.6 (1.1)	31.2 (0.1)	20.8^a (1.3)	26.1^a
BS1	28.2^b (0.4)	29.9 (4.4)	31.5 (0.8)	24.6^b (1.1)	28.6^b
BS2	25.1^a (1.4)	24.6 (2.4)	31.0 (0.3)	24.6^b (1.5)	26.3^a
BS3	26.3^{ab} (1.0)	24.5 (1.1)	31.9 (1.1)	21.2^a (1.3)	26.0^a
P (site)					<0.05
P (treatment)	<0.05	ns	ns	<0.01	<0.01
P (site × treatment)					<0.05
Equilibrium water infiltration rate (mm h^{-1})					
Control	335 (141)	88 (22)	187 (92)	50 (25)	165
BS1	1,149 (389)	140 (74)	195 (113)	88 (34)	393
BS2	1,055 (161)	72 (30)	139 (39)	50 (9)	329
BS3	1,041 (149)	156 (57)	168 (72)	124 (54)	372
P (site)					<0.001
P (treatment)	ns	ns	ns	ns	ns
P (site × treatment)					ns

continues

TABLE 3. Continued

	Bridgets	Gleadthorpe	Rosemaund	Woburn	All sites
Aggregate stability (% dispersion ratio)					
Control	3.3^{c} (0.6)	3.1 (1.3)	5.8 (0.6)	11.9 (1.1)	6.0
BS1	3.2^{bc} (0.2)	6.0 (0.1)	4.9 (0.5)	10.3 (1.1)	6.1
BS2	2.3^{ab} (0.2)	5.4 (1.3)	4.7 (0.9)	10.5 (1.5)	5.7
BS3	2.2^{a} (0.4)	4.0 (0.8)	4.7 (0.3)	8.8 (0.8)	4.9
P (site)					<0.001
P (treatment)	<0.05	ns	ns	ns	ns
P (site × treatment)					ns

Values in parentheses are standard errors (n = 3). Treatments labeled with different superscript letters are significantly ($P < 0.05$) different from each other. For description of treatments see Table 2.

ns, Not significant.

respectively (given a soil bulk density of 1.3 g cm^{-3}), and indicated that 35% to 60% of the OM added in the biosolids (i.e., 33 t ha^{-1}) had been retained in the topsoil. Using data from 10 long-term experimental studies (4–18 years), Powlson et al. (2012) reported an average increase in soil organic carbon of 180 kg C ha^{-1} y^{-1} tds^{-1} from the application of digested biosolids. This was three times higher than the rate for farm manures (60 kg C ha^{-1} y^{-1} tds^{-1}), indicating that biosolids applications are a good source of stable OM for building up SOM levels. Given the interest in exploring potential land management strategies for increasing soil carbon (or SOM) storage in the mitigation of climate change, these organic material retention coefficients are useful for improving national greenhouse gas inventory methodologies (Maillard and Angers, 2014).

The LFOM is a transitional pool of OM within soils, which includes partially decomposed OM from organic material additions (Gregorich et al., 1997). 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 (Malhi et al., 2003; Bhogal et al., 2011). There were again significant ($P < 0.001$) differences in LFOM between the sites and no significant site × treatment interactions ($P > 0.05$; Table 3). At all four sites, there were numerical increases in LFOM from the BS2 additions compared with the inorganic fertilizer control, although this could only be confirmed statistically at Bridgets. However, when all the sites were considered together, there was a highly significant ($P < 0.001$) increase in LFOM on the BS2 treatment (2.9 g kg^{-1} compared with 1.8 g kg^{-1} on the untreated control; Table 3).

The cross-site analysis showed that the biosolids treatments also increased ($P < 0.05$) the soil CEC compared with the untreated control on the BS1 and BS2 treatments (Table 3) because the additional OM supplied with these biosolids applications increased the electrostatic surface charge available to attract and hold cations.

Changes in Physical Properties

Additions of OM with biosolids have been shown to improve soil physical properties such as soil structure and water-holding capacity (e.g., see Lu et al., 2012). Organic matter also helps to bind soil mineral particles into crumbs (or aggregates), thus improving the stability of the soil and its resistance to erosive forces.

In this study, differences in OM inputs with biosolids led to significant ($P < 0.01$) treatment differences in soil moisture contents at permanent wilting point and field capacity (data not shown) and in

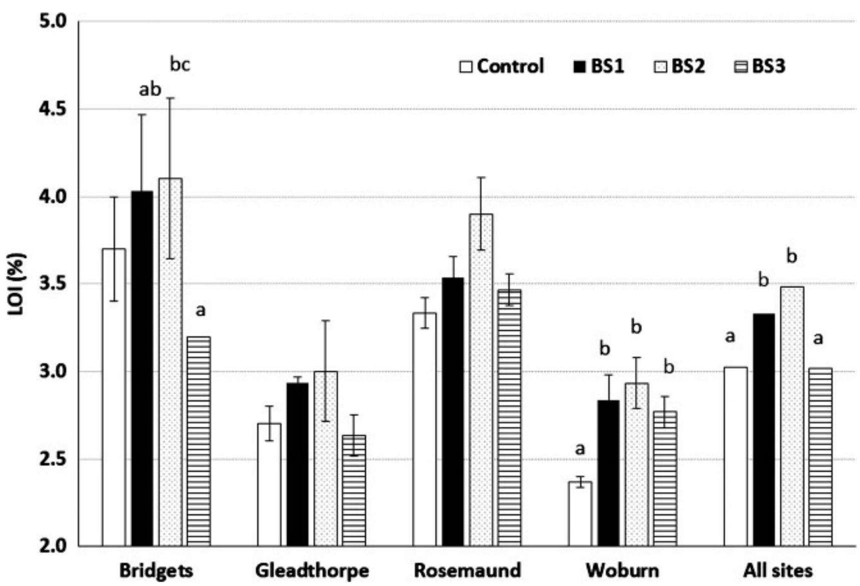

FIGURE 1. Effect of biosolids applications on SOM measured using LOI (error bars show standard errors; columns labeled with different letters are significantly ($P < 0.05$) different from each other). For description of treatments, see Table 2.

TABLE 4. Mean Topsoil Total N, Potentially Mineralizable N, P Fractions, and Total S at Each Site in 2014

	Bridgets	Gleadthorpe	Rosemaund	Woburn	All Sites
Total N (%)					
Control	0.20 (<0.01)	0.13 (<0.01)	0.16[a] (0.01)	0.09[a] (<0.01)	0.14[a]
BS1	0.19 (0.01)	0.14 (<0.01)	0.17[ab] (0.01)	0.12[b] (0.01)	0.16[bc]
BS2	0.22 (0.03)	0.14 (0.01)	0.19[b] (0.01)	0.11[b] (0.01)	0.17[c]
BS3	0.22 (0.01)	0.12 (0.01)	0.17[a] (0.01)	0.11[b] (0.01)	0.15[ab]
P (site)					<0.001
P (treatment)	ns	ns	<0.05	<0.05	<0.01
P (site × treatment)					ns
PMN (mg kg^{-1})					
Control	50.0[a] (3.3)	43.7 (5.1)	34.3 (5.5)	23.5[a]	37.9
BS1	63.1[b] (1.5)	51.1 (8.0)	38.2 (3.9)	33.9[bc]	46.6
BS2	68.9[b] (4.7)	48.8 (10.8)	53.7 (10.0)	29.3[b]	50.2
BS3	59.6[b] (1.2)	41.4 (5.1)	44.8 (21.6)	35.6[c]	45.4
P (site)					<0.001
P (treatment)	<0.05	ns	ns	<0.01	ns
P (site × treatment)					ns
Olsen extractable P (mg L^{-1})					
Control	46[a] (3.5)	47[a] (1.5)	31[a] (3.7)	67[a] (1.0)	48[a]
BS1	54[a] (5.9)	66[b] (1.9)	44[a] (7.0)	97[c] (2.9)	65[c]
BS2	67[b] (6.4)	64[b] (3.8)	61[b] (12.1)	91[c] (1.0)	71[d]
BS3	55[a] (4.7)	59[b] (3.1)	40[a] (2.7)	83[b] (2.9)	59[b]
P (site)					<0.001
P (treatment)	<0.05	<0.05	<0.05	<0.001	<0.001
P (site × treatment)					<0.05
Resin extractable P (mg L^{-1})					
Control	56.5 (9.7)	61.8 (0.4)	40.9[a] (2.3)	58.1[a] (3.7)	54.3[a]
BS1	79.8 (na)*	71.9 (5.9)	56.9[bc] (8.5)	101.8[b] (1.6)	77.6[c]
BS2	78.7 (0.7)**	73.3 (5.6)	63.4[c] (9.8)	88.5[b] (3.5)	76.0[c]
BS3	67.3 (4.9)	72.4 (7.5)**	44.4[ab] (2.0)	81.6[b] (8.8)	67.0[b]
P (site)					<0.01
P (treatment)	ns	ns	<0.05	<0.05	<0.001
P (site × treatment)					ns
0.1 *M* NaOH extractable P (organic) (mg L^{-1})					
Control	186 (45)	171 (34)	109 (9)	171 (20)	159[a]
BS1	161 (33)	230 (24)	168 (43)	256 (17)	204[bc]
BS2	204 (45)	206 (13)	208 (17)	262 (21)	220[c]
BS3	207 (32)	190 (18)	123 (12)	177 (22)	174[ab]
P (site)					ns (0.06)
P (treatment)	ns	ns	ns (0.06)	<0.05	<0.05
P (site × treatment)					ns

continues

TABLE 4. Continued

	Bridgets	Gleadthorpe	Rosemaund	Woburn	All Sites
Total S (mg kg^{-1})					
Control	264^{a} (4.0)	204 (11.6)	208^{a} (21.7)	146^{a} (5.2)	206^{a}
BS1	324^{b} (11.6)	260 (4.2)	207^{a} (30.4)	216^{c} (12.0)	252^{c}
BS2	312^{b} (9.4)	252 (19.1)	283^{b} (11.5)	209^{c} (13.9)	264^{c}
BS3	306^{b} (8.1)	209 (7.5)	199^{a} (35.7)	190^{b} (10.1)	226^{b}
P (site)					<0.01
P (treatment)	<0.05	ns (0.06)	<0.05	<0.001	<0.001
P (site × treatment)					ns

Values in parentheses are standard errors (n = 3). Treatments labeled with different superscript letters are significantly ($P < 0.05$) different from each other. For description of treatments, see Table 2.

*One replicate.

**Two replicates.

na, Not available; NaOH, bicarbonate; ns, not significant.

AWC relative to the untreated control. In particular, topsoil AWC was significantly increased ($P < 0.05$) by the BS1 and BS2 applications to the light textured soil at Woburn (Table 3). However, there was a significant ($P < 0.05$) site × treatment interaction indicating that this effect is likely to be strongly dependent on soil conditions at a particular site.

There was also a (nonsignificant) trend toward higher water infiltration rates at some sites and treatments ($P = 0.07$; Table 3), indicating that the biosolids additions could decrease the potential for surface water runoff and the susceptibility of the soils to water erosion and associated sediment losses.

Aggregate stability (assessed using the dispersion ratio method) is a measure of the soil's ability to resist disruptive forces. At Bridgets, the BS2 and BS3 treatments increased aggregate stability to a small extent ($P < 0.05$), as shown in the lower dispersion ratio values (Table 3). There were also numerical reductions in the dispersion ratios for all the biosolids treatments at Rosemaund and Woburn, although these could not be confirmed statistically, even when all sites were considered together ($P > 0.05$; Table 3).

Other studies have reported increased water retention and aggregate stability after biosolids application, although very high application rates of up to 300 t ha^{-1} were sometimes used (Lu et al., 2012), and the magnitude of the observed effects will clearly depend strongly on the type and quantity of the materials applied as well as on the characteristics of the receiving soil. Nevertheless, these findings indicate that biosolids additions at normal agronomic rates can help to improve soil stability and play an important role in allowing more water to infiltrate into soils more quickly, reducing irrigation volumes and helping to reduce peak flows into watercourses (and hence flooding risk).

Effects of Biosolids on Soil Nutrient Supply

Most agricultural soils contain too little plant-available N to meet the needs of a crop throughout the growing season, and hence farmers supply N in the form of mineral fertilizers. Biosolids are known to contain valuable quantities of crop-available N, which can replace some of the required mineral fertilizer N. This is indeed one of the major reasons why biosolids are recycled to agricultural land. Biosolids also contain N in organic forms, which is not immediately available for crop uptake but can help to build soil total N stocks in the longer term. Across all the sites, the BS1 and BS2 treatments led to significant ($P < 0.01$) increases in topsoil total N contents (Table 4), reflecting the much greater quantities of N applied with these products (approximately 3 t ha^{-1}) compared with the BS3 biosolids (approximately 0.8 t ha^{-1}).

Potentially mineralizable N is a biological measure of the soils' capacity to supply N through the mineralization of soil organic N reserves to ammonium-N and can consequently be converted to nitrate-N (by nitrification processes). Potentially mineralizable N provides an indication of the N that will be released in the short to medium term and has importance for fertilizer recommendations. In this study, PMN concentrations were increased ($P < 0.05$) on all the biosolids treatments at Bridgets and Woburn, with numerical increases on some treatments at Gleadthorpe and Rosemaund (Table 4). This provides good evidence that biosolids organic N can be mineralized to plant-available forms, contributing to crop N requirements and reduced mineral N fertilizer costs.

A recent review by Rigby et al. (2016) found that the amount of mineralizable N in biosolids depends on the treatment process (i.e., the extent of biological stabilization) and varies across climatic regions. These authors concluded that some international fertilizer recommendations may underestimate the amount of mineralizable N in biosolids and hence their fertilizer N value. More work is therefore needed, particularly from field studies, to better quantify N mineralization in different biosolids products and to ascertain when the N is mineralized in relation to crop growth and development (i.e., can the N released be utilized by the growing crop, or would it remain in the soil and be subject to over-winter nitrate leaching losses?).

Phosphorus is also an essential plant nutrient, but unlike N, the P applied in biosolids generally moves slowly through the soil, which can hold large quantities in forms that are available for crop uptake over several years. Olsen-extractable P (and resin-P) provides a measure of the amount of P available for crop uptake, and all sites had a moderate to high concentration (31 to 97 mg L^{-1}, Table 4). Extractable P concentrations were increased on the BS2 treatment at all four sites ($P < 0.05$; Table 4), reflecting the greater amount of P applied (1.7 t ha^{-1}) compared with the BS1 (1.2 t ha^{-1}) and BS3 (1.1 t ha^{-1}) treatments; this was confirmed by significant increases in grain P (Table 5). There was a significant site × treatment interaction for extractable P, indicating the observed effects are likely to be strongly dependent on conditions at a particular site. Nevertheless, these findings indicate that biosolids can provide a valuable source of P (and reduce the need for manufactured P fertilizer) on soils low in P.

The results of the P fractionation showed that not only did biosolids additions significantly increase the amount of inorganic P readily available for plant uptake (i.e., Olsen-P and resin-P),

TABLE 5. Grain Total N, P, and S Concentrations at Each Site in 2014

	Bridgets	Gleadthorpe	Rosemaund	Woburn	All Sites
Grain total N (%)					
Control	2.2^a (0.02)	1.7^a (0.07)	1.4 (0.06)	1.5 (0.03)	1.70^a
BS1	2.3^b (0.06)	2.1^b (0.13)	1.6 (0.07)	1.5 (0.02)	1.88^b
BS2	2.4^b (0.01)	1.9^{ab} (0.09)	1.7 (0.10)	1.5 (0.03)	1.86^b
BS3	2.2^a (0.02)	1.7^a (0.05)	1.6 (0.07)	1.4 (0.02)	1.72^a
P (site)					<0.001
P (treatment)	<0.05	<0.05	ns	ns (0.05)	<0.001
P (site × treatment)					ns
Grain total P (mg kg^{-1})					
Control	2,851 (194)	3,719 (118)	3,006 (171)	2,670 (168)	3,062^a
BS1	3,245 (28)	3,821 (72)	3,033 (144)	2,964 (32)	3,266^{ab}
BS2	3,355 (104)	4,054 (51)	2,922 (216)	3,405 (145)	3,434^b
BS3	3,324 (40)	3,951 (140)	3,107 (238)	2,901 (133)	3,321^b
P (site)					<0.001
P (treatment)	ns (0.08)	ns	ns	ns (0.05)	<0.05
P (site × treatment)					ns
Grain total S (mg kg^{-1})					
Control	1,189^a (22)	1,258 (19)	881 (35)	1,075 (58)	1,101^a
BS1	1,286^b (20)	1,304 (14)	987 (54)	1,016 (16)	1,148^a
BS2	1,354^c (25)	1,364 (50)	951 (36)	1,241 (21)	1,227^b
BS3	1,268^b (15)	1,261 (33)	933 (34)	1,062 (95)	1,131^a
P (site)					<0.001
P (treatment)	<0.05	ns (0.06)	ns	ns	<0.001
P (site × treatment)					ns

Values in parentheses are standard errors (n = 3). Treatments labeled with different superscript letters are significantly ($P < 0.05$) different from each other. For description of treatments, see Table 2.

ns, Not significant.

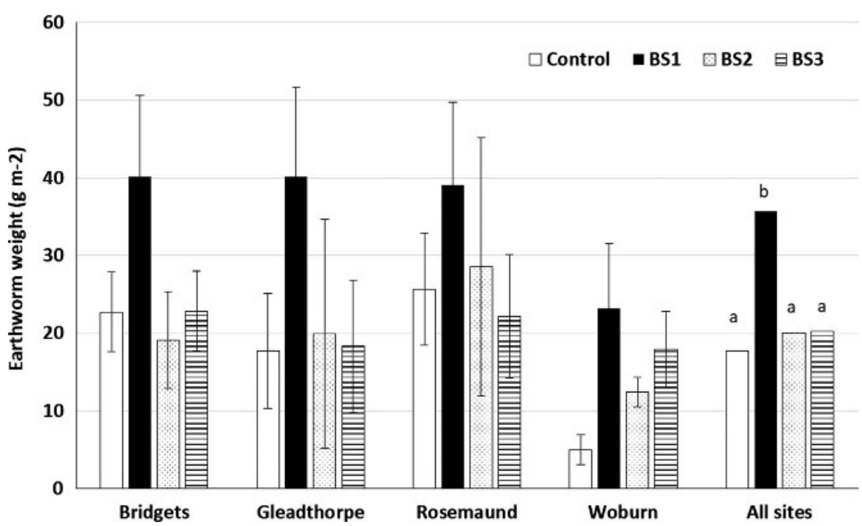

FIGURE 2. Effect of biosolids applications on earthworm weight (error bars show standard errors; columns labeled with different letters are significantly ($P < 0.05$) different from each other). For description of treatments, see Table 2.

but they also increased the amount of moderately available organic P (i.e., extractable with 0.1 *M* NaOH, Table 4). If soil fertility falls, these organic P forms can be mobilized by soil microbes to provide a source of P for crop growth. Biosolids inputs can therefore provide both short- and long-term sources of soil P for plant uptake. However, care must be taken to avoid excessive levels of soil P (i.e., Olsen-$P > 25$ mg L^{-1}), as this can pose a risk of phosphate transfer from soil to surface waters, contributing to eutrophication (Withers et al., 2016). These authors suggested that the release of P to run-off water (i.e., the eutrophication risk) depends on both the biosolids type and the soil and that biosolids could be more sustainably managed by matching applications to soil type and P fertility status.

At all sites except Rosemaund, soil total S concentrations were higher on all the biosolids treatments compared with the untreated control ($P < 0.001$; Table 4), highlighting the importance of biosolids as a source of this essential crop nutrient and supporting findings from previous studies that biosolids contain useful quantities of S, which can make a significant contribution to crop S requirements (Sagoo et al., 2014). As previously discussed, biosolids treatments also increased the soil CEC (Table 3), which is related to improved soil nutrient retention and hence fertility.

Effects of Biosolids on Earthworms

Earthworms have a major influence on soil quality because of their role in breaking down OM, improving soil structure, and allowing water/oxygen to move through the soil profile. In general, farming systems that provide greater OM returns to the soil support higher earthworm populations (Scullion et al., 2002). However, Kinney et al. (2012) suggested that inconsistent results from field studies with respect to the effects of organic manures on earthworm populations were a result of variations between the applied materials (in both nutrient and potentially toxic compound concentrations), as well as differences in soil characteristics.

In this study, the number and weight (Fig. 2) of earthworms were found to have approximately doubled where BS1 biosolids (which had a low metal content) were applied. Importantly, the BS2 and BS3 treatments, which had elevated concentrations of Zn and Cd, respectively, did not decrease the number of earthworms relative to the untreated control. These findings are supported by those from a recent study (Coors et al., 2016), which found only weak evidence for negative long-term effects on soil fauna (nematodes, enchytraeids, and earthworms) of biosolids applied at commercial rates.

Crop Yields and Quality

Although there was no statistically significant yield response to biosolids, grain yields were numerically higher on all the biosolids treatments at Gleadthorpe, Rosemaund, and Woburn, with yield increases of up to 1.2 t ha^{-1} measured on the light sandy soil at Woburn.

Grain total N, P, and S concentrations were increased where biosolids had been applied at all sites (Table 5), suggesting that an increase in supply of these essential plant nutrients from the biosolids applications may explain the yield and crop growth differences observed. Increased N, P, and S supply from the biosolids therefore provided an additional nutrient "boost" to the crops, even though the recommended rates of mineral fertilizers had been applied to all treatments. Increases in AWC (and hence increased crop water and nutrient supply) and improved soil structure (facilitating increased rooting) at some sites and treatments may also have contributed to increases in crop nutrient uptake (Table 3).

At Bridgets, where the wheat grown was of bread-making quality, biosolids applications significantly increased grain S concentrations (Table 5), which has been shown to be related to improved bread quality in terms of dough elasticity and loaf volume (Zhao et al., 1999a,b). There were no negative effects of the biosolids applications on the taste or texture of bread produced from the wheat grown at Bridgets, or on the quality and taste of the beer produced from the barley grown at Gleadthorpe (data not shown). These findings suggest that biosolids have the potential to improve wheat grain quality, but may require careful management to maintain the quality of malting barley (where lower grain N is required).

CONCLUSIONS

Experimental plots with a history of biosolids additions (20 years) supplying approximately between 12 and 33 t ha^{-1} OM were used to assess the effects of repeated biosolids additions on soil biophysical and physicochemical properties. Increases in SOM following the long-term biosolids additions were accompanied by a number of improvements in soil physical (AWC, aggregate stability, water infiltration rate), chemical (soil N, P, and S supply; CEC) and biological properties (earthworm numbers and weight), and crop quality (grain N, P, and S concentrations). No negative effects on crop quality were reported following the long-term biosolids additions. The results from this study have provided valuable evidence toward maintaining a sustainable agricultural landbank for biosolids recycling in the United Kingdom and have been incorporated into Best Practice Guidance (UKWIR, 2015).

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