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RESEARCH ARTICLE

A new sludge-derived organo-mineral fertilizer gives similar crop yields as conventional fertilizers

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Abstract Sewage sludge, a waste material commonly known as biosolids, has good potential as a valuable agricultural resource, providing that its nutrient imbalances could be overcome. Sewage sludge is rich in phosphorus but low in nitrogen and potassium. Technology exists to supplement sewage sludge with mineral fertilizers, such as urea and muriate of potash as sources of nitrogen and potassium, respectively, to produce an organo-mineral fertilizer with balanced crop nutrient requirements. Here, an experimental plot trial set up in 2008 was established at Broxton, Cheshire, UK, to compare crop yield response for typical crop varieties. Crops included wheat, oilseed rape, barley, beans and forage maize, treated with conventional fertilizer and organo-mineral fertilizer. The organo-mineral fertilizer is a nutrient-balanced sludge-based product produced by drying digested sewage sludge cake at 80 °C in a tumbling evaporator, which produces sludge granules of 3–6 mm in diameter. Analysis was carried out on soil NPK and crop yield. N use efficiency was measured to assess N uptake. Results show that there is no significant difference in crop yield between treatments over the three trial years, with the exception of one crop. This finding demonstrates that the new organo-fertilizer is as efficient as conventional fertilizers. Moreover, levels of heavy metal in soil did not exceed permissible levels. The novelty of this research lies in the fact that it is the first field scale trial of a modified sewage sludge product that has the potential to transform a hitherto waste product into a practical fertilizer product. We conclude that the organo-mineral fertilizer is a promising alternative product for sustainable agriculture.

Keywords Organo-mineral fertilizer · Conventional fertilizer · Biosolids · Crop yield · Nutrients

1 Introduction

Over 9.4 million tonnes of sewage sludge are produced annually in the European Union (EU; EEA 2005 estimate), and with a growing population, this amount will increase. How to deal with these quantities of domestic sewage sludge and make provision for future growth raises social, environmental and ethical questions. More traditional routes of disposal such as disposal at sea were banned by the EU Urban Waste Water Treatment Directive 91/271/EC (CEC 1991) or greatly restricted by the EU Landfill Directive 99/31/EC (CEC 1999) that required a 75 % reduction in biodegradable waste going to landfill between 1995 and 2010. Alternative disposal routes such as incineration are believed to be unsustainable and have met strong public opposition at planning stage (Petts 1994). The disposal of

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the ash from incinerated sewage may also contain high concentrations of heavy metals and other toxins that require careful disposal (Wei et al. 2003).

An alternative to disposal is to recycle this resource as an agricultural fertilizer, but this has a number of disadvantages. Sewage sludge (or biosolids) has a highly variable fertilizer potential (Sommers 1977), not only does the nutrient value vary but the rate of nutrient release is also difficult to predict making it hard to manage both from an agronomic and environmental perspective. There are also concerns regarding heavy metal concentrations in sewage sludge and potential accumulation of these heavy metals in the soil with the potential for subsequent transfer to crops (Johnston 2008). In addition, the relatively low N/P ratio of biosolids can lead to a build-up of soil phosphorus when applied at a rate needed to meet crop nitrogen requirements (Edge 1999).

There is clearly a case to be made for finding ways around the issues associated with using sewage sludge as an agricultural resource, in order to overcome the primary problem of disposal of a waste product. In addition, recycling organic waste will help offset the demise of finite resources of phosphorus that are under pressure from an expanding world population that needs feeding. There are various estimates of the global phosphate resource; however, realistically the true figure is largely unknown. This is partly because of the sensitive nature of the information, and partly because there may be phosphate rock yet to be discovered (Cordell et al. 2009; Hilton et al. 2010). Sewage sludge also contains substantial amounts of other important plant nutrients including nitrogen, sulphur, magnesium and micro nutrients (MAFF 2000). In addition, organic fertilizers have advantages over mineral fertilizers in that their use improves soil structure, drainage, available water and builds up organic matter (EA 2004), which helps promote plant growth. The long-term Woburn Market Garden Experiment, which started in 1942, studied the effects of application of sewage sludge on the yield response of horticultural vegetables. This showed that the application of organic manure produced large increases in yield in the crops tested, except for peas, and the responses were generally larger than the responses to fertilizer N on the plots without organic manures (Johnston and Wedderburn 1974). Gibbs et al. (2006) reported on a shorter-term field trial involving application of sewage sludge, which ran for 4 years and noted that there was no significant impact to soil microbial activity. Nicholson et al. (2006) carried out an inventory of inputs of heavy metals in agricultural soils in England and Wales and reported the highest heavy metal input rates on a field basis were generally from sewage sludge. However, the studies by Gibbs et al. (2006) and Nicholson et al. (2006) did not focus on the crop yield response to application of sewage sludge. In the current work, soil samples were analysed at two depths, 0–30 and 30–60 cm, and analysed for nickel, cadmium, mercury and chromium. Whilst these elements had increased and decrease at the two depths, the overall levels were within the maximum permissible levels according to the Code of Good Agricultural Practice (MAFF 1998). Consequently, heavy metals are not the focus of this current paper.

The use of amendments such as sewage sludge in agriculture supports the concept of sustainable intensification of agriculture. The definition of “sustainable agriculture,” in its modern approach, can be traced back to the USA in the early 1980s, indicating a way of farming that should mimic natural ecosystems (Gomiero et al. 2011). In the last decades, in order to face the challenge to feed 9 billion people by 2050, a concept called “sustainable intensification” has been discussed, meaning producing more food from the same area of land while reducing the environmental impacts (Pretty 2002, 2008; Royal Society of London 2009; Godfray et al. 2010).

As part of the UK Government's Foresight Global Food and Farming project, 40 projects and programmes in 20 countries involving sustainable intensification have been developed during the 1990s–2000s. By early 2010, these projects had documented benefits for 10.4 million farmers and their families and improvements on approximately 12.75 million ha. Food outputs by sustainable intensification have been multiplicative—by which yields per hectare have increased by combining the use of new and improved varieties and new agronomic–agroecological management (crop yields rose on average by 2.13-fold), and additive—by which diversification has resulted in the emergence of a range of new crops, livestock or fish that added to the existing staples or vegetables already being cultivated (Pretty et al. 2011).

This current study focuses on the use of an organo-mineral fertilizer (Fig. 1) that overcomes problems associated with variable nutrient content and imbalances in N/P ratio in sewage sludge by combining the organic material with an inorganic coating of urea and supplement of potassium (Antille 2011). Organo-mineral fertilizers have previously been

Fig. 1 Organo-mineral fertilizers shown as pellets that were used in this project

proven to be a good alternative fertilizer product for wheat and forage maize crops (for example, Ayeni et al. 2012; Ailincăi et al. 2008), but to our knowledge, these previous trials do not use a combination of anthropogenic sewage sludge with mineral fertilizers. Another advantage of organo-mineral fertilizers is that the mineral components are protected by the binding and absorption of organic components which results in a more gradual release of nutrient to the soil and the reduction of nutrient losses to the environment (FAO 2007). This paper reports the crop yield response over a 3-year field trial that compared conventional fertilizer application with the use of a novel organo-mineral fertilizer treatment. Figure 2 shows how both fertilizers were applied on field plots. We hypothesized that there will be differences in crop yield between organo-mineral fertilizer and a conventional one. The trial was established to mimic realistic farming scenarios found in the geo-climatic region where the trial was established. The rationale behind this was to ensure that the results would be meaningful to the end user community. The main aim of this research is to ultimately reduce the reliance on inorganic fertilizers and increase the use of organic amendments such as sewage sludge in a sustainable agricultural production system.

2 Materials and methods

2.1 Field site

An experimental field site was established at Broxton, northwest England, in 2008 (Fig. 3). The field site has a generally flat topography with a slight (<1°) incline in a westerly direction that is located in an area that has a typical annual rainfall of 1,250–1,500 mm and an average annual maximum temperature of 13–14 °C. The soil within the field belongs to the Clifton Association (Ragg et al. 1984), which consist of slowly permeable seasonally waterlogged reddish fine and coarse loamy soils, defined as a Stagnic Luvisol soil under the World Reference Base classification system. This soil type is typically used for cereals and grassland.

2.2 Field plots

In 2008, following a winter wheat crop, 1.6 ha of a 5-ha field was marked out into 48 plot areas each 288 m^2 (Fig. 3). Prior to crop establishment, a 750-g, baseline, soil sample taken at 0–30 cm was collected from each plot area and bulked into one sample bag for soil chemical analysis using standard soil laboratory protocols (see Section 2.6). Subsequently, rotational crop systems were established in the plot areas. The rotation sequences and crop varieties chosen were typical of the geo-climatic region in which the experiment was established. This choice enabled the experimental plots to be used in demonstration events hosted for local farmers as the trial had direct relevance to their farming systems. The crop rotations included winter wheat, Einstein and Solstice (*Triticum aestivum* L.); spring wheat Tybolt (*T. aestivum* L.); all oilseed rape, Ability (*Brassica napus* L.); winter barley Sequal (*Hordeum vulgaris* L.); spring beans Fuego (*Phaseolus vulgaris* L.); forage maize, ES Ballade (*Zea mays L.*) as shown in Table 1. The remaining field area was sown with perennial rye grass mix in 2008. The arable plots were laid out between tramlines (24 m

Fig. 2 Spreader applying fertilizers in plots at Broxton, Cheshire, UK

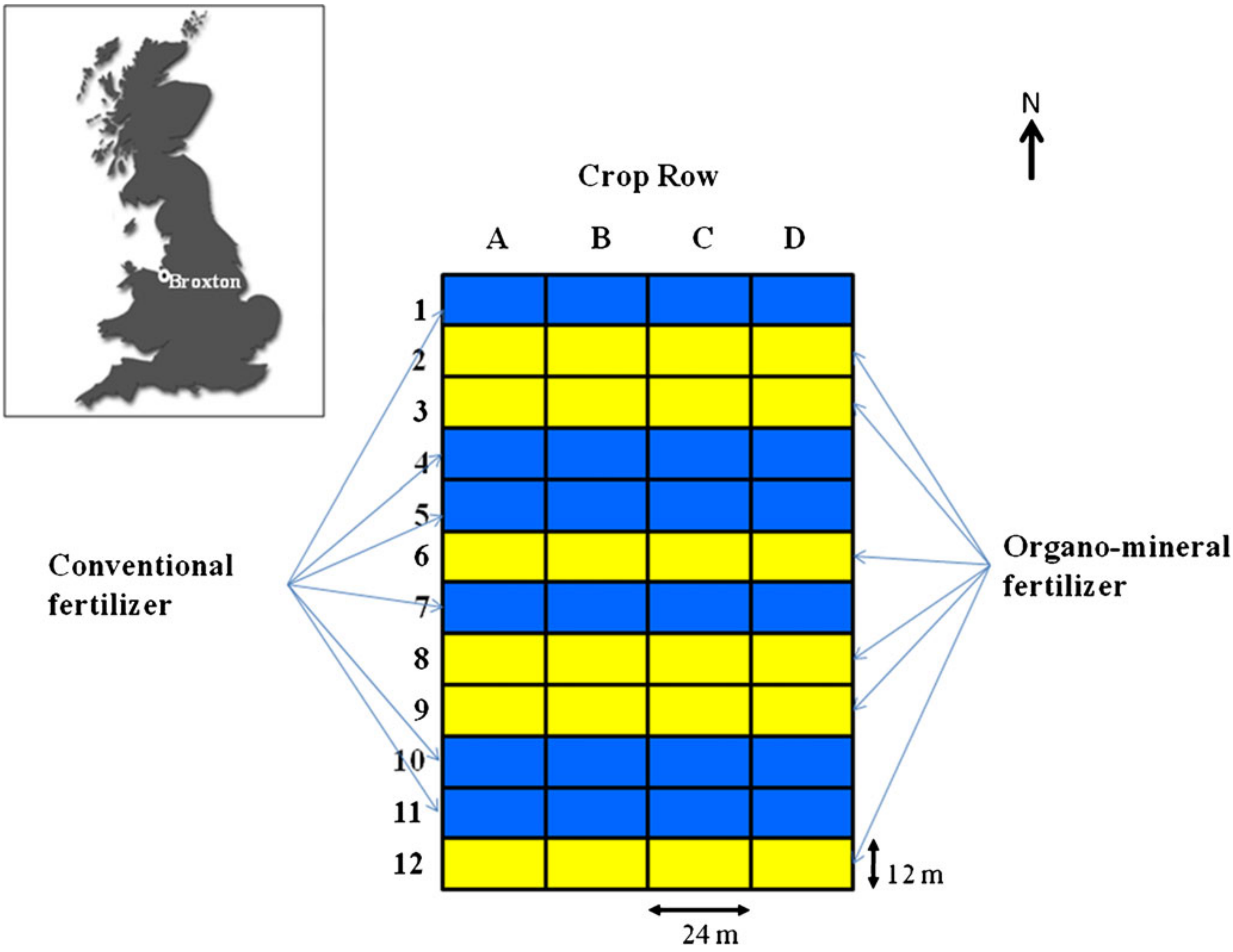

Fig. 3 Location of experimental field site at Broxton, UK and experimental plot design showing 24-m-wide crop rows (*A*, *B*, *C* and *D*) running vertically and 12-m-long fertilizer application plot rows running horizontally (not drawn to scale). Crops in plot rows *1*, *4*, *5*, *7*, *10* and *11* have conventional fertilizer applied, while crops in plot rows *2*, *3*, *6*, *8*, *9* and *12* have organo-mineral fertilizer applied

wide), which were used to traffic the field during routine crop treatment such as spraying of herbicides and fungicides (Fig. 3). A yearly post-harvest soil sample was collected from 0–30 cm in 2009, and 2010 samples were bulked according to crop type and fertilizer treatment; however, in 2011, soil analysis was performed on each plot. Soil chemical analysis of the samples was performed using standard soil laboratory protocols (see Section 2.6).

2.3 Fertilizer

A conventional fertilizer treatment was compared with a novel organo-mineral fertilizer treatment.

2.4 Conventional fertilizer

Combinations of single nutrient mineral fertilizers were used to provide the recommended nutrient requirements. Nitrogen and potassium were applied as ammonium nitrate (Nitram 34 % N) and muriate of potash (60 % K_2O), respectively. No additional phosphorus fertilizer was added as the soil contained adequate levels (24 mg l^{-1} Olsen-P; P index 2).

2.5 Organo-mineral fertilizer

United Utilities Water, which is a public limited company (PLC), in collaboration with Cranfield University under the Knowledge Transfer Partnership scheme has recently developed a novel method of blending mineral fertilizers with sewage sludge to produce an organo-mineral fertilizer called SMART-P^{TM} (Antille 2011). The organo-mineral fertilizer is a nutrient-balanced sludge-based product produced by drying digested sewage sludge cake at 80 °C in a tumbling evaporator, which produces sludge granules of between 3 and 6 mm in diameter.

Table 1 Crop rotations from 2008 to 2011 based on typical crop sequences used in the geo-climatic region

Year	Crop row			
	A	B	C	D
2008/2009	Forage maize	Oilseed rape	Winter wheat 1	Winter wheat 2
2009/2010	Spring oilseed rape	Winter wheat	Spring wheat	Forage maize
2010/2011	Oilseed rape	Spring beans	Winter barley	Winter wheat

Supplementary mineral nutrients (such as urea and muriate of potash as source of nitrogen and potassium, respectively) were added to provide a higher proportion of available nutrients in the product. The proportion of these additional nutrients can be varied to take account of the variable nutrient content of the raw biosolid. The biosolids used in this study contained 3 % (standard deviation=0.63) total nitrogen, 5.86 % (standard deviation=0.84) total phosphorus (P, Olsen-P) and 0.18 (standard deviation=0.18) total potassium based on dry matter weight (Gedara et al. 2009). The supplementary mineral nutrients were added as coating to the sludge granules by spray application of steam melted urea granules in a rotary drum mixer. Further drying produced a *c.* 90 % dry solid content. The nutrient content (based on dry matter weight) of the prototype batch used in this trial contained 14.08 % (standard deviation=0.18) total nitrogen, 3.74 % (standard deviation=0.20) total phosphorus (P, Olsen-P) and 0.05 % (standard deviation=0.25) total potassium (K_2O) (Gedara et al. 2009). The product also contained 1.61 % sulphur and 0.50 % magnesium (Gedara et al. 2009). This prototype product does not yet incorporate potassium as a coating directly; therefore, potassium was applied separately using muriate of potash (60 % K_2O). The novelty of this product lies in the approach of blending two sources of fertilizers (i.e. sewage sludge that is a renewable resource) and a reduced source of inorganic fertilizer (such as urea and muriate if potash).

2.6 Fertilizer treatment

Figure 3 shows the distribution of the two fertilizer treatments across the experimental plots. This plot design was used consistently throughout the project. Each strip of crop (crop row A to D) was sub-divided into twelve 12-m-wide plots between a series of secondary tramlines at right angles to the main tramlines. Each strip of crop had six replicates of each fertilizer treatment, which were randomly allocated down the strip but not between strips to reduce the amount of trafficking over the field area. Both fertilizer treatments were applied using a 12-m pneumatic boom spreader. Pre-application calibration of the pneumatic boom spreader was performed by capturing and weighing expelled granules in a container over a known time (with boom arm removed). Homogeneity of organo-mineral fertilizer granule distribution was calculated by placing three sets (placed 10 m apart) of nine collecting trays (dimensions 0.5×0.5×0.15 m) across the operating working width of the spreader boom. Dispersal spread was assessed at a flow rate of 455 kg (organo-mineral fertilizer)ha^{-1} applied from a tractor driven at 5 miles per hour in accordance with standard operational procedure. The weights of granules collected in each tray were compared using an ANOVA analysis. Calibration tests showed that application for all products was even across the boom width with no statistical difference ($p=0.572$) at a 95 % confidence interval between the quantity of product collected in test trays. Although the organo-mineral fertilizer was sieved prior to application, to ensure the correct size distribution of granules, dust was produced during the application process, indicating additional product refinement is necessary to produce a more stable granule.

Rate of application of fertilizer was based on Kemira GrowHow N-Min assessment for nitrogen application rates, and all other nutrient recommendations were based on RB209 (MAFF 2000) following good agricultural practices. Application rates of the organo-mineral fertilizer were based on the assumption that the product was completely dry (100 % dry solids), the standard practice for inorganic fertilizer products. However, it was later discovered that the prototype organo-mineral fertilizer product actually contained 10 % moisture, resulting in a slightly lower nutrient application for the organo-mineral fertilizer treatment than the conventional treatment.

Phosphorus was not added as part of the conventional fertilizer treatment because there was sufficient reserve of phosphorus in the soil; however, phosphorus is present in the organo-mineral fertilizer product. Ammonium nitrate (30 kg ha^{-1}) was added, by broadcast application, in the first year to the winter wheat as part of the organo-mineral fertilizer treatment in early March 2009 because of a delay in the delivery of the organo-mineral fertilizer granules.

The application of conventional or organo-mineral fertilizers was carried out at the same time according to advice from an agronomist following conventional practice. The application of both fertilizers occurred around late March and late May as split application for nitrogen, whilst potassium was applied as a single dose in late May.

2.7 Crop yield

Cereal, oilseed rape and bean crops were harvested using a Wintersteiger Seedmaster plot combine, whilst forage maize was harvested using a front mounted Champion 1200 forage harvester. For all crops a 3-m strip was cut east to west using farm machinery to delineate the end of the plots, and then yield was assessed by harvesting two north to south 1.5-m strips from each 24-m plot; the actual plot length combined was recorded at harvest and the yield in tonnes per hectare calculated. Representative samples were taken at harvest for moisture and quality assessment for all crops. Moisture content was assessed in drying ovens at 105 °C for 24 h then checked for weight loss over an hour, for cereals and beans. The moisture content of forage maize samples (whole crop weight) was assessed by force ventilation of a 500–700-g sample at 20 °C for 24 h followed by a further 24 h at 60 °C. Values were normalized to standard moisture contents based on dry matter weight. Standard moisture contents for wheat, beans and barley were 15 %, for forage maize (whole crop yield), 67 % and for oilseed rape, 6 %. These post-harvest drying methodologies are based on standard protocols accepted by the Department for Environment, Food and Rural Affairs (Defra) as laid down for National List Trials in the UK. Maize is dried at 60 °C in order for near-infrared spectroscopy analysis of the sample.

2.8 Analytical methods

Soil samples were analysed using standard soil analysis methods, expressed as values relating to volume of soil. Soil phosphorus was measured using the Olsen P method, solution spectrophotometry after complexing with ammonium molybdate (Murphy and Riley 1962). Potassium was extracted using 1 M ammonium nitrate and assessed using flame emission spectrometry (MAFF 1986). Calcium was extracted using 1 M ammonium nitrate and analysed using atomic absorption (MAFF 1986). Manganese was extracted using 1 M ammonium acetate with 2 g l^{-1} guinol and analysed using atomic absorption (ISO 11047, 1998). Sulphur was extracted using calcium tetrahydrogen diorthophosphate and analysed using solution spectrophotometry of precipitated barium sulphate (MAFF 1986). Copper was extracted using 0.05 M EDTA disodium salt and analysed using atomic absorption (ISO 11047, 1998). Zinc was extracted using 0.05 EDTA disodium salt and analysed using atomic absorption (ISO 11047, 1998). Soil acidity (pH) was based on water extraction and determined using a pH electrode meter (ISO 10390, 1994). The cation exchange capacity was determined by leaching the soil with 1 M ammonium acetate followed by 10 % potassium chloride and measured using an ion-specific electrode. Sugar and starch content of forage maize were determined using near-infrared spectroscopy. Maize kernels were initially prepared by drying at 60 °C before being milled to 3 mm and a 50-g subsample taken and milled to 1 mm.

2.9 Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 19. One-way ANOVA analysis was used to test the significant difference between treatments for crop yields and soil properties (for 2011) using a 95 % confidence level. Mean values were based on six observation of either crop weight or chemical concentration for each of two treatments, conventional fertilizer and organo-mineral fertilizer. For crop yield, comparisons were made between treatments for a given crop type. For soil, chemical concentrations were compared between treatments for a given crop and to the initial baseline chemical value.

3 Results and discussion

3.1 Crop yield response

With the exception of one crop, winter wheat (year 2008/2009, crop row C), treatment differences in yield were observed but were not significantly different (at a 95 % confidence level). Figure 4 shows the absence of effect on yield between the different fertilizer treatments. The mean yields (Table 2) were generally compatible with typical yields for the UK (Nix 2011), although oilseed rape crops were slightly lower than UK average yields and the spring oilseed rape crop in 2009/2010 failed due to adverse weather conditions. Spring beans and winter barley yield were also slightly lower than UK average in 2010/2011. For winter wheat (year 2008/2009, crop row C) where significant differences were observed between treatments, the mean yield from crops receiving organo-mineral fertilizer treatment was approximately 20 % lower than the crop yield from the conventional fertilizer plots. However, comparison of the weight of 1,000 grains of wheat (44.1 g conventional treatment and 42.0 g organo-mineral fertilizer per 1,000 grains) showed no significant difference ($p=0.379$). This implies that yield difference must be due to fewer grains per unit area on organo-mineral fertilizer-treated plots. The timing of nitrogen application and nitrogen availability are known to affect yield (Alley et al. 2009). As similar amounts of nitrogen were applied using organo-mineral fertilizer and conventional fertilizer treatments, the rate and timing of release of the nutrient may have been the influencing factors. Figure 5 shows the comparison of maize plots applied with the two fertilizer types.

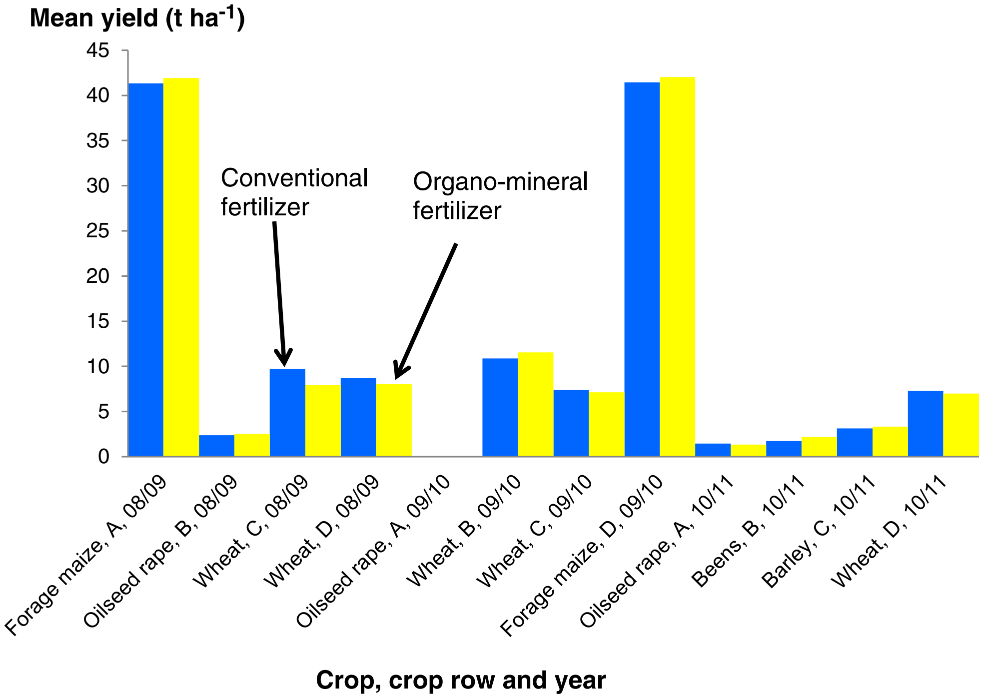

Fig. 4 Comparison of mean crop yields between the two fertilizer treatments of conventional fertilizer and organo-mineral fertilizer, for each crop row (A, B, C and D) over the 3-year trial (2008 to 2011)

3.2 Nitrogen use efficiency

Johnston and Poulton (2009) discussed several indices and methods used to determine the efficiency at which plant nutrients are used in crop production. One of the indexes relevant in this work is the partial factor productivity of applied nitrogen (I_P) and is calculated as the ratio between the kilogram of product obtained per kilogram N applied; therefore, $I_P = \frac{Y_N}{N_{Rate}}$ where Y_N refers to yields of the crop (kilogram grain per hectare) corresponding to the treatment ($N \neq 0$), and N_{Rate} is the nitrogen application rate (kilograms N per hectare). The I_P of forage maize in 2008/2009 for organo-mineral fertilizer and conventional fertilizer were 349.2 and 344.2 kg crop kg^{-1} N. The change in I_P was minimal for maize in 2009/2010 where 350 and 345 kg crop kg^{-1} N were calculated for organo-mineral fertilizer and conventional fertilizer, respectively. The I_P for winter wheat associated with organo-mineral fertilizer and conventional fertilizer, respectively, were 40.5 and 49.7 kg grain kg^{-1} N (2008/2009), 59.0 and 55.9 (2009/2010) and 35.9 and 37.4 (2010/2011). The values of I_P between both fertilizers were very close and support the argument that no significant difference in yield was observed. This provides further evidence to support the assumption that organo-mineral fertilizer are comparable to conventional fertilizer in terms of crop use of nitrogen from these two sources. Biosolid fertilizers provide a slow-release nutrient supply to crops (Gendebien et al. 2010). One potential explanation could be that with repeated application of organo-mineral fertilizers, there would be a build-up of soil fertility, which influences the soil microbial community to be more active in mineralising the nutrients locked up in organo-mineral fertilizers (Petersen et al. 2003). In addition to this, there are also other nutrients such as sulphur and magnesium present in organo-mineral fertilizers which can further boost mineralisation of nitrogen.

3.3 Soil analysis

Results of the soil analysis (see Tables 3 and 4) show that prior to sowing the experimental crops, the soil had a pH of 7.1, adequate phosphorus levels (24 mg l^{-1}; P index 2) but low levels of potassium (115 mg l^{-1}; K index 1), according to Defra (2010) recommendations. Sulphur (5 mg l^{-1}) and manganese (39 mg l^{-1}) levels were also low. However, calcium (2,204 mg l^{-1}) levels were above the recommended level of 1,600 mg l^{-1}. The cation exchange capacity of the soil at the start of the trial was14.1 meq 100 g^{-1}, which indicates a slightly low nutrient holding capacity for this soil.

In 2011, where soil analysis was performed on each plot area, there was no significant difference in pH, phosphorus, potassium, sulphur, calcium or manganese concentration between treatments for the four crop rows (Table 4) and generally no significant difference between baseline measurements and crop row treatments, with three exceptions. Manganese concentration from organo-mineral fertilizer plots in crop row A was significantly lower (34.1 mg l^{-1}) than the baseline value, and pH for organo-mineral fertilizer plots in crop row C was significantly lower (6.9) than the

Table 2 Comparison by fertilizer treatment of yields normalised to standard moisture content of crop based on dry matter

Year	Crop	Row	*n*	Treatment	Mean yield (t ha^{-1})	Std. error mean	Significance
2008/2009	Maize[a]	A	6	OMF	41.9	2.08	0.874
			6	CF	41.3	2.97	
	Oilseed[b]	B	6	OMF	2.5	0.11	0.564
			6	CF	2.4	0.18	
	W Wheat[c]	C	6	OMF	7.9	0.59	0.035[d]
			6	CF	9.7	0.45	
	W Wheat[c]	D	6	OMF	8.0	0.84	0.612
			6	CF	8.7	0.95	
2009/2010	S Oilseed[b]	A	6	OMF	–	–	–
			6	CF	–	–	
	W Wheat[c]	B	6	OMF	11.5	0.64	0.448
			6	CF	10.9	0.54	
	S Wheat[c]	C	6	OMF	7.1	0.68	0.708
			6	CF	7.4	0.19	
	Maize[a]	D	6	OMF	42.0	0.72	0.642
			6	CF	41.4	0.95	
2010/2011	Oilseed[b]	A	6	OMF	1.3	0.30	0.785
			6	CF	1.4	0.19	
	S Beans[c]	B	6	OMF	2.2	0.34	0.568
			6	CF	1.7	0.68	
	W Barley[c]	C	6	OMF	3.3	0.24	0.647
			6	CF	3.1	0.66	
	W Wheat[c]	D	6	OMF	7.0	0.26	0.534
			6	CF	7.3	0.38	

CF Conventional fertilizer, *OMF* Organo-mineral fertilizer

[a] Forage maize, mean whole crop yield at 67 % moisture content;

[b] Oilseed rape, mean grain yield at 6 % moisture content

[c] Wheat, beans and barley, mean grain yield at 15 % moisture content

[d] Significantly different at a 95 % confidence level

baseline value, while phosphorus concentrations in crop row B were significantly lower (20.81 mg l^{-1}) in conventional fertilizer plots than the baseline value.

Phosphorous (P) levels in 2008/2009 showed increases in the soil samples taken from crop row C plots (winter wheat), conventional fertilizer and organo-mineral fertilizer, which both showed increased levels of P above baseline (Table 4). As no additional P was added as part of the conventional fertilizer treatment, it must be concluded that these results reflect a higher initial residual P concentrations at this location in the field than was captured by the bulked baseline dataset. A single application of de-watered sewage sludge will supply adequate PO_4^{3-} for most 3–4 year crop rotations (Smith 2008).

Fig. 5 Comparison of maize plots applied with organo-mineral fertilizers (*left*) and conventional fertilizer (*right*). The maize plots applied with organo-mineral fertilizer look more lush and green compared to the conventional one

Table 3 Annual fertilizer application to meet crop-based requirements

Row	Year	Crop	Treatment	Annual total (kg ha^{-1})		
				N	P	K
1	2008/2009	Forage maize	CF	120	0	100
			OMF	120	31	100
	2009/2010	Oilseed rape	CF	70	0	60
			OMF	70	15	60
	2010/2011	Oilseed rape	CF	70	0	70
			OMF	70	15	70
2	2008/2009	Oilseed rape	CF	105	0	70
			OMF	105	30	70
	2009/2010	Winter wheat	CF	195	0	70
			OMF	195	51	70
	2010/2011	Spring beans	CF	0	0	70
			OMF	15	31	70
3	2008/2009	Winter wheat	CF	195	0	70
			OMF	195	51	70
	2009/2010	Spring wheat	CF	195	0	70
			OMF	195	51	70
	2010/2011	Winter barley	CF	120	0	70
			OMF	120	31	70
4	2008/2009	Winter wheat	CF	195	0	70
			OMF	195	51	70
	2009/2010	Forage maize	CF	120	0	100
			OMF	120	31	100
	2010/2011	Winter wheat	CF	195	0	70
			OMF	195	51	70

CF Conventional fertilizer, *OMF* Organo-mineral fertilizer

Potassium (K) levels also spiked above the baseline concentration in crop rows B, C and D in 2008/2009 (wheat and oilseed rape) where organo-mineral fertilizer and conventional fertilizer treatments were applied (Table 4); however, no differences were expected as K was added as Muriate of Potash for both organo-mineral fertilizer and conventional fertilizer treatments. Sulphur (S) levels remained similar to baseline levels in all treatments except for oilseed rape, in 2008/2009, where higher S levels than baseline occurred for both organo-mineral fertilizer and conventional fertilizer treatments (Table 4).

4 Conclusion

Despite application of nutrients being slightly lower using organo-mineral fertilizer compared to conventional fertilizer, because of the moisture content within the product, growth response to the different treatments was generally not significantly different at this site. Concentrations of nutrients in the soil at this site also remained similar to the initial baseline levels with no significant differences in accumulation of nutrients between the two treatments. However, it is recommended that further experiments on a variety of sites, which cover a range of fertility levels, should be conducted in order to fully examine the potential of the product.

Nutrient use efficiency calculations using partial factor productivity of applied nitrogen showed values which were comparable between conventional and organo-mineral fertilizers. This indicates that crop nitrogen uptake is efficient using organo-mineral fertilizers despite its organic source. This indicates improved soil fertility possibly associated with increased soil microbial activity that assists in mineralization of nutrients from organo-mineral fertilizers.

The novel organo-mineral fertilizer product was applied uniformly using a standard pneumatic boom spreader, although there was an issue associated with particle breakdown causing dust during application, which needs to be resolved. From an end-user perspective, this means that no specialist equipment would need to be purchased in order to use this product. Equipment already used to apply conventional fertilizer should be appropriate. The product could be further enhanced by enabling potassium to be incorporated as a coating onto the product rather than having to be applied as a separate

Table 4 Soil pH, phosphorus, potassium, sulphur, calcium and manganese concentrations for the different crop rows and fertilizer treatments over the 3-year trial period

	Year	Crop row and fertilizer treatment								Baseline (2008)
		A		B		C		D		
		CF	OMF	CF	OMF	CF	OMF	CF	OMF	
pH	2009	6.8	6.6	7.1	7.3	6.9	6.8	6.7	6.8	7.1
	2010	7.3	7.1	7.1	7.1	7.2	7.1	7.1	7.0	
	2011	6.9	6.9	6.8	6.8	6.9	6.9[a]	6.8	6.8	
P (mg l^{-1})	2009	24	24	22	25	42	30	24	22	24
	2010	24	20	20	20	22	21	18	13	
	2011	22	22	21[a]	20	22	21	18	19	
K (mg l^{-1})	2009	119	115	156	183	122	140	130	142	115
	2010	116	94	129	110	123	96	100	95	
	2011	97	89	109	90	100	99	86	96	
S (mg l^{-1})	2009	8	8	13	27	7	6	6	7	5
	2010	7	4	4	5	5	4	3	3	
	2011	5	6	6	7	6	7	10	11	
Ca (mg l^{-1})	2009	2,347	2,271	2,370	2,509	2,102	2,153	2,095	2,229	2,204
	2010	2,431	2,110	2,259	2,321	2,243	2,403	2,203	2,028	
	2011	2,116	2,102	1,976	1,653	2,199	2,137	2,139	2,142	
Mn (mg l^{-1})	2009	27	31	36	37	38	27	26	28	39
	2010	41	37	47	40	32	34	48	44	
	2011	34	34[a]	40	38	39	41	37	37	
Cu (mg l^{-1})										
	2011	5.0	5.0	4.5	4.6	4.6	4.8	4.8	4.8	4.5
Zn (mg l^{-1})										
	2011	4.2	4.0	3.6	3.6	4.0	3.8	3.5	3.7	4.6

CF Conventional fertilizer, *OMF* Organo-mineral fertilizer

In 2011, soil analysis was recorded for each plot area, and statistical analysis was performed

[a] Values that are significantly different from the baseline data at a 90 % confidence interval

nutrient. The coating procedure used means that the variable nutrient concentrations of sewage sludge can be overcome and can also be adjusted to meet specific crop requirements.

While sewage sludge may contain variable amounts of nutrients making their use as a fertilizer less predictable, the transformation of sewage sludge through combination with mineral fertilizers to an organo-mineral fertilizer product has been shown to be a promising step forward in converting a waste material into a commercially viable agricultural fertilizer. The novelty in producing this wholesome fertilizer from a renewable resource without compromising crop yield is a key feature of this work which also aims to support sustainable intensification of agriculture.

This manuscript also sets the scene for future experimental work where it is possible to convert waste into resource. However, challenges include ensuring the heterogeneity of the waste material which will influence the reproducibility of the final product (an alternative fertilizer in this case). In the current project since the waste water treatment plants were stringent in ensuring the influent was from certain sources, some control was exerted on the treatment process and finally the sludge that was produced. Regulations and policies in place also help to provide a greater control on the quality of sludge that is being produced. Collectively, these influence the quality and consistency of the organo-mineral fertilizer which is derived from sludge material.

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