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Agronomic Value of Alkaline-Stabilized Sewage Biosolids for Spring Barley

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ABSTRACT

Land application of sewage biosolids is a cheap disposal method that permits recycling of plant nutrients, but there are concerns about its long-term agronomic value and environmental effects. This study investigated the fertilizer value of alkaline-stabilized biosolids applied annually to spring barley (*Hordeum vulgare* L.). Dewatered biosolids [320–350 g kg⁻¹ dry matter (DM)] were alkaline stabilized by mixing them with cement kiln dust and composting aerobically. The product had some liming value (300 g kg⁻¹ DM CaCO₃ equivalent on average) and contained an average of 7.2, 2.3, and 19.5 g kg⁻¹ DM of N, P, and K. Two field experiments compared the P or K value of the biosolids with inorganic fertilizer P or K for seven consecutive annual spring barley crops on two contrasting soils. All biosolid and fertilizer treatments gave higher yields than the controls. Biosolids gave higher grain and straw yields than fertilizer P, similar grain and straw yields to fertilizer K, and higher grain weights and more grains per ear than fertilizer P or K. These effects may have been due to, *inter alia*, higher soil pH and S inputs. An increasing soil pH from biosolid application was associated with lower shoot Mn concentrations, but no Mn deficiency symptoms were observed. Alkaline biosolids acted as a slow-release P fertilizer, and biosolid P was at least as available to the crops as inorganic fertilizer P. Biosolid K was also as available as fertilizer K. A calculation of nutrient balances indicated that current fertilizer P recommendations could be lowered.

THE USE OF ALKALINE-STABILIZED BIOSOLIDS as organic fertilizers or soil conditioners has become widespread in the USA. The *N-viro soil* process (Burnham et al., 1992) involves mixing biosolids with quicklime and cement kiln dust (an inorganic waste material from precipitators in cement factories) and quicklime followed by accelerated drying. Besides cement kiln dust, other alkaline wastes can be used such as lime kiln dust, limestone, and coal fly ash (Burnham et al., 1992; Wong et al., 1995). The resulting products can be used as substitutes for agricultural limestone, organic fertilizers in land reclamation, soil amendments for landscaping, ingredients in the manufacture of synthetic topsoils, and substitutes for soil landfill cover (Logan and Burnham, 1995; Logan and Harrison, 1995; Pierzynski and Schwab, 1993; Sloan and Basta, 1995; Stehouwer et al., 1999; Wong, 1995).

Much of the published research on alkaline-stabilized biosolids has largely been concerned with the application of potentially toxic trace metals to soils. Logan and

Harrison (1995) found that the physical properties of a silt loam of pH 6.5 could be improved with high application rates of N-viro soil. In a glasshouse study, Pierzynski and Schwab (1993) found that N-viro soil applied at the rate of 5 Mg DM ha⁻¹ decreased Zn in the soil labile fraction and Zn, Cd, and Pb concentrations in soybean [*Glycine max* (L.) Merr.] plants. Sloan and Basta (1995) reported that N-viro soil effectively remediated soil acidity and Al toxicity in three highly acidic soils. Wong (1995) showed that mixtures of alkaline fly ash and biosolids mixed with loam soil decreased the availability of Zn, Cu, and Cd to tall wheatgrass [*Elytrigia elongata* (Host) Nevski] plants in a pot experiment and increased plant yield. In contrast, Sajwan et al. (1995) found increased concentrations of Cu and Zn in sorghum/sudangrass hybrid plants in a loamy sand amended with a mixture of coal fly ash and sewage biosolids. One problem with using coal fly ash is its relatively high concentration of B. Relatively low concentrations of B can be phytotoxic, especially to cereals, and B may affect plant growth when high application rates of biosolids stabilized with fly ash are used.

The Water Service of the Department of the Environment for Northern Ireland has developed the *agri-soil* process for the alkaline stabilization and aerobic composting of sewage sludge solids before land spreading as a means of sludge disposal. The initial pH of the biosolid mixture and kiln dust rises above 11.0 to kill pathogens and suppress odors and declines to about 7.8 after composting. Heat generated during the composting stage further contributes to pathogen kill and increases the DM content of the final product. The composted biosolids contain less N and P than raw sludge biosolids, but they have a relatively high K content that is derived from the kiln dust. They also have a neutralizing value (CaCO₃ equivalent) of 300 g kg⁻¹ on average (DM basis). The process is relatively inexpensive and can easily be automated.

Although alkaline products can remediate heavy metal phytotoxicity by raising soil pH, there is still concern about the long-term accumulation of trace metals in agricultural soils. The European Union banned sea dumping of sewage biosolids at the end of 1998, and all member states have legal regulations imposing maximum limits on the total metal concentrations in agricultural soils (e.g., U.K., 1989). Agri-soil was developed for agricultural use by using rural batches of sewage biosolids with lower metal loadings than urban or industrial sources. Manganese deficiencies have been reported in some crops on coarse-textured soils receiving alkaline biosolids in the USA, and foliar application of

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Abbreviations: ANOVA, analysis of variance; DM, dry matter; OM, organic matter.

Mn to soybeans and wheat (*Triticum aestivum* L.) has led to crop yield responses (Brown et al., 1997).

There is little published information on the agronomic value of alkaline biosolids, especially under U.K. conditions. This paper outlines the agri-soil process and describes two long-term field experiments on contrasting soils in which the agronomic value of the alkaline biosolids for spring barley was investigated in seven consecutive annual crops. One experiment was conducted on a basaltic clay soil with low available P status and was designed to evaluate the P value of different application rates of alkaline biosolids. The other experiment investigated the K value of the biosolids applied to a shale clay loam with low exchangeable K. Some of the preliminary results from the first 5 yr of the K experiment have been reported briefly (Christie and Easson, 1997). Nutrient balances were calculated for P and K to determine the optimum reserves in the two soils. The chemical speciation and bioavailability of trace metals from alkaline biosolids that were applied to the two soils in glasshouse studies have been reported (Luo, 1997; Luo and Christie, 1997, 1998). Soil samples collected from the plots of the field experiments in February 1999 are currently being analyzed for trace metal concentrations and speciation, and those results will be reported in a separate paper dealing with the uptake of trace metals by the crops.

MATERIALS AND METHODS

The Agri-Soil Process

The agri-soil process was developed by Love (1990) and is shown schematically in Fig. 1. Rural batches of sewage sludge that are screened and picket-fence thickened are mixed with an anionic or cationic polyacrylamide polyelectrolyte solution to act as a flocculent and then passed through a modified belt press. Each batch of sludge must be tested to determine whether it should be treated with an anionic or cationic flocculent. The solids (300–350 g kg⁻¹ DM) are then mixed in a ratio of 65:35 w/w fresh weight with cement kiln dust. The mixture is composted by turning daily in windrows under cover for 5 d to produce a short-term sanitized but organically unstabilized material with a DM content of 500 to 550 g kg⁻¹. This can then be turned regularly in the open for another 45 d to achieve organic stability and a DM content of 750 to 800 g kg⁻¹. This process differs from the N-viro soil process (Burnham et al., 1992) developed in the USA in its use of composting rather than accelerated drying. It is essential to dewater the sludge solids to a relatively high DM content (>300 g kg⁻¹) to achieve a successful composting stage. Once organic stability has been achieved, the alkaline biosolids can be stored outdoors indefinitely without any deterioration in chemical or physical properties.

The Field Experiments

The P experiment was established on a basaltic clay (Typic Haplaquept) at Muckamore near Antrim, Northern Ireland

Fig. 1. Agri-soil process flow diagram.

(Irish Grid Reference J170839). Alkaline biosolids were applied each year to plots (2.5 by 15 m) at rates of 17, 34, 51, and 68 Mg DM ha⁻¹. Triple superphosphate was applied to identical plots at rates of 17, 35, 52, and 70 kg P ha⁻¹, which were calculated to give approximately the same range of available-P application rates as the organic amendment, assuming 50% availability of total sludge P on average (Simpson, 1986, p. 90–99). The actual application rates of total sludge P averaged 38, 75, 112, and 150 kg ha⁻¹ year⁻¹ (calculated over the first six crops because the total P in the biosolids used in 1998 was not determined). The range of P application rates studied was selected to cover the range of U.K. fertilizer recommendations for soils of low P status to soils of high available P status (Ministry of Agriculture, Fisheries, and Food, 1994). Control plots received no P applications, but supplementary N and K were applied where necessary to prevent yield responses to N or K on the basis of current U.K. fertilizer recommendations (MAFF, 1994). Before the first crop in 1992, ground limestone (3 Mg ha⁻¹) was applied to all plots to raise the soil pH to 6.4, the target value for an *organic* soil [16 g kg⁻¹ organic matter (OM)] (MAFF, 1994). The biosolids, inorganic fertilizers, and ground limestone were thoroughly incorporated into the top 15 cm of the soil profile before sowing the barley seeds.

The K experiment had a similar design and was established in 1992 at Corcreeny near Hillsborough in Down, Northern Ireland (Irish Grid Reference J208588) on a sandy loam derived from Silurian shale and Triassic sandstone (Typic Dystrachrept). Alkaline biosolids were applied to plots (4 by 20 m) at rates of 4, 8, 12, and 16 Mg DM ha⁻¹. Potassium chloride was applied to other plots at application rates of 42, 83, 124, and 166 kg K ha⁻¹, which were calculated to give approximately the same range of K application rates as the organic amendment. Fertilizer K application rates were based on an analysis of biosolid batches made in early 1992; however, subsequent batches were higher in K and the actual application rates of K in the sludge product averaged 80, 160, 240, and 320 kg ha⁻¹ from 1992 to 1997. Controls received no K applications, but supplementary N and P were applied where necessary to bring the total application of N and P up to recommended rates for barley in the United Kingdom (MAFF, 1994) so that any yield responses could not be attributed to N or P. Ground limestone was applied (2 Mg ha⁻¹) to all plots to raise the soil pH to 6.7, the target value for the mineral soil (4 g kg⁻¹ OM) (MAFF, 1994).

The plots were plowed each year to incorporate the fertilizer or biosolids into the soil. Plowing was done in opposite directions in alternate years to limit the mixing of the soil in adjacent plots to the edges of the plots. All plant and soil samples were collected from the central part of each plot to avoid edge effects. Spring barley (cv. Forrester in 1992 and 1993 and cv. Chariot from 1994–1996) was grown at both sites. The crops were grown using all recommended inputs of herbicides, pesticides, and growth regulators for optimum yield. There were four replicates of nine treatments in a fully randomized block, giving a factorial design of 2 × 4 + control and a total of 36 plots at each site.

Plant and Soil Analysis

Shoot samples were collected at the tillering stage for nutrient analysis. At harvest, the grain and straw from the center of each plot were collected and weighed, and the subsamples were retained for oven drying and chemical analysis. Subsamples of grain from the K experiment were used to determine the proportion of dirt present (avg. <20 g kg⁻¹), the hectoliter weight, and the 1000-grain weight. Plant, tiller, and head densities were counted.

Soil properties were determined on composite samples collected to a 15-cm depth every February using standard methods (MAFF, 1986). Plant N was determined by standard dry combustion using a CHN Analyzer. Other plant nutrients were determined by inductively coupled plasma–atomic emission spectrometry (ICP-AES) following digestion in a mixture of nitric and perchloric acids using standard methods (MAFF, 1986). Quality control of all analytical methods was monitored using standard reference materials and by participation in the International Plant and Soil Analytical Exchange Programs.

Statistical Analysis

The mean yield, grain quality, grain and straw nutrient concentrations and offtakes at harvest, and shoot nutrient concentrations at the tillering stage were tested for seven consecutive annual crops by analysis of variance (ANOVA) in a 2 × 4 + control factorial design. In addition, the effects of time (growth year) were tested by repeated-measures ANOVA; the data for all seven crops were combined, and the variance ratios in the time stratum were multiplied by the calculated Greenhouse–Geisser epsilon values before determining the significance levels (Genstat Committee, 1993). The rate degrees of freedom were broken out into orthogonal contrasts, and some of the linear contrasts of the rate factor were found to be significant.

RESULTS

The DM and major nutrient concentrations in the batches of alkaline biosolids that were applied from 1992 to 1998 are presented in Table 1. The product varied widely in DM content (378–775 g kg⁻¹), reflecting differences in composting time before delivery to the sites. The batches applied in 1995 and 1996 were fully composted and organically stabilized, but the material

Table 1. Dry matter (DM), N, P, and K composition of the batches of alkaline biosolids used from 1992 to 1998, and the mean annual application rates of these major elements.

Site	Date	DM	N	P	K
		g kg ⁻¹	g kg ⁻¹ DM		
Antrim:	1992	482	12.28	2.57	17.4
Basaltic till	1993	494	5.94	1.05	18.1
clay with low	1994	414	6.56	2.77	18.1
available P	1995	775	5.85	2.68	22.3
status	1996	769	5.40	2.40	12.4
	1997	595	5.36	1.71	26.9
	1998	450	ND†	ND	ND
		kg ha ⁻¹			
Mean annual application rate:					
17 Mg Biosolids DM ha ⁻¹			117	37	326
34 Mg Biosolids DM ha ⁻¹			234	75	653
51 Mg Biosolids DM ha ⁻¹			352	111	979
68 Mg Biosolids DM ha ⁻¹			469	150	1306
			g kg ⁻¹ DM		
Hillsborough:	1992	482	12.28	2.57	17.4
Silurian shale	1993	509	9.02	2.20	23.7
sandy loam	1994	378	6.85	2.46	15.6
with low	1995	775	5.85	2.68	22.3
available K	1996	769	5.40	2.40	12.4
status	1997	595	5.36	1.71	26.9
	1998	450	ND	ND	ND
		kg ha ⁻¹			
Mean annual application rate:					
4 Mg Biosolids DM ha ⁻¹			30	9	79
8 Mg Biosolids DM ha ⁻¹			60	19	158
12 Mg Biosolids DM ha ⁻¹			90	28	237
16 Mg Biosolids DM ha ⁻¹			120	37	316

† ND, not determined.

Fig. 2. Mean annual grain-response curves to increasing application rate of fertilizer and biosolid P at the Antrim site.

used in other years was only partially stabilized and would have continued to decompose after incorporation into the soil. The concentrations of N, P, and K, expressed on a DM basis, also varied by two to threefold among batches. The average annual application rates of N and K at Antrim were high because of the high application rates of biosolids required to cover the desired range of P application rates. Sulfur was not analyzed in the alkaline biosolids. If we assume a similar S content in the freshly dewatered biosolids to the average for farmyard manure ($10 \text{ g S kg}^{-1} \text{ DM}$; Simpson, 1986, p. 90–99) and take into account the ratio of biosolids/cement kiln dust (containing 50 g S kg^{-1}) and the mean DM content of the alkaline biosolids used, we can calculate that the biosolids contained up to $35 \text{ g S kg}^{-1} \text{ DM}$ on average. This also assumes no loss of S by volatilization during composting. This gives an estimated range of S application rates up to about 600 to $2400 \text{ kg ha}^{-1} \text{ year}^{-1}$ at Antrim and 140 to $560 \text{ kg ha}^{-1} \text{ year}^{-1}$ at Hillsborough.

Mean annual grain yields with increasing application rates of fertilizer P or biosolids at the Antrim site are plotted in Fig. 2. Both the inorganic and organic sources of P gave yield responses compared with the control, and the biosolids gave a higher yield response than the fertilizer. Similarly, both sources of K produced grain

Fig. 3. Mean annual grain-response curves to increasing application rate of fertilizer and biosolid K at the Hillsborough site.

yield responses at the Hillsborough site, but these responses were similar for both fertilizer and biosolids (Fig. 3).

Annual grain and straw yields, grain weights, and some plant population data for both sites are presented in Table 2. There was always a significant yield response or increase in other parameters determined to the lowest application rate of fertilizer or biosolids compared with the control at both sites (except for plant density at Hillsborough). However, there were never further significant responses to higher application rates, and therefore the data presented are averaged over all four rates of fertilizer or biosolids. The only variable for which a significant orthogonal contrast was found was straw yield at the Antrim site. The significant linear contrast indicates an increase in straw yield with increasing P application rates at this site. When averaged over the seven crops, biosolids produced higher grain and straw yields and higher grain hectoliter weights than fertilizer P on the basaltic clay. Alkaline biosolids also gave similar grain and straw yields and higher grain weights and numbers per ear compared with fertilizer K at Hillsborough. The density of barley plants, tillers, and heads was the same using fertilizer K and biosolids. Grain and

Table 2. Mean annual yields of grain (15% moisture content basis) and straw (dry matter basis), grain hectoliter wt., and thousand grain wt. (TGWT) at Antrim and Hillsborough, and number of grains ear⁻¹ and plant population data at Hillsborough for seven consecutive annual spring barley crops grown from 1992 to 1998. At Antrim, hectoliter wt.'s were not recorded from 1992 to 1995, and TGWTs were not determined from 1993 to 1995.

Treatment	Antrim: Basaltic clay				Hillsborough: Silurian shale and Triassic sandstone sandy loam							
	Grain yield	Straw yield	Hectoliter weight	TGWT	Grain yield	Straw yield	Hectoliter weight	TGWT	Grain number	Plants	Tillers	Heads
	— Mg ha ⁻¹ —		kg	g	— Mg ha ⁻¹ —		kg	g	no. ear ⁻¹		no. m ⁻²	
Control	3.61	1.57	59.7	35.7	4.47	2.18	62.9	36.4	17.5	325	818	608
Fertilizer	4.51	1.85	61.4	37.6	5.20	2.58	63.6	37.3	18.0	328	909	659
Biosolids	4.99	2.28	62.5	37.8	5.37	2.49	64.4	37.6	18.4	329	918	670
Significance†:												
Treatment	***	**	***	***	***	***	***	***	***	NS	***	**
P or K source	***	***	***	NS	NS	NS	***	***	**	NS	NS	NS
P or K level	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year	***	***	***	***	***	***	***	***	***	***	***	***
Year × treatment	*	NS	*	*	***	***	*	***	**	NS	***	NS
Year × source	**	***	NS	***	***	**	NS	**	*	NS	NS	NS

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† By ANOVA; year stratum analyzed by repeated measures ANOVA.

Table 3. Mean grain and straw conc.'s and annual offtakes of N, P, K, and S from 1992 to 1998.

Site and crop component	Conc.				Offtake			
	N	P	K	S	N	P	K	S
	g kg ⁻¹				kg ha ⁻¹			
Antrim grain								
Control	17.7	2.94	5.10	1.35	55.1	9.3	15.9	4.24
Fertilizer	17.0	3.36	5.00	1.31	66.0	13.1	19.5	5.13
Biosolids	18.1	3.76	5.41	1.43	78.3	16.2	23.3	6.19
Significance:								
Treatment vs. control	NS	***	NS	NS	***	***	***	***
Fertilizer vs. biosolids	***	***	***	***	***	***	***	***
Application rate	*	***	NS	NS	NS	**	NS	NS
Year	***	***	***	***	***	***	***	***
Year × treatment	NS	NS	NS	NS	NS	NS	NS	NS
Year × form of P	**	NS	NS	NS	**	*	NS	**
Antrim straw								
Control	7.07	0.54	14.1	1.52	11.0	8.4	22.5	2.42
Fertilizer	5.74	0.63	11.6	1.40	10.6	11.4	22.7	2.79
Biosolids	6.68	0.87	18.3	2.67	15.5	19.2	45.1	6.35
Significance:								
Treatment vs. control	***	***	***	***	*	***	**	***
Fertilizer vs. biosolids	***	***	***	***	***	***	***	***
Application rate	*	***	***	NS	**	***	*	NS
Year	***	***	***	***	***	***	***	***
Year × treatment	NS	NS	NS	NS	NS	NS	NS	NS
Year × form of P	*	NS	NS	**	**	*	***	**
Hillsborough grain								
Control	13.7	3.54	4.92	1.12	54.0	13.7	19.5	4.40
Fertilizer	14.2	3.52	4.86	1.11	64.1	15.8	22.2	5.04
Biosolids	15.0	3.76	5.00	1.22	69.7	17.6	23.7	5.71
Significance:								
Treatment vs. control	**	**	NS	*	***	***	***	***
Fertilizer vs. biosolids	***	***	***	***	**	***	**	***
Application rate	NS	NS	NS	NS	NS	NS	NS	NS
Year	***	***	***	***	***	***	***	***
Year × treatment	**	NS	NS	NS	***	***	***	***
Year × form of K	**	NS	NS	**	***	***	***	***
Hillsborough straw								
Control	4.63	0.74	9.3	9.5	10.3	1.48	20.3	2.05
Fertilizer	4.44	0.66	11.6	9.5	11.3	1.63	30.6	2.47
Biosolids	4.83	0.78	12.5	18.5	11.8	1.92	31.7	4.74
Significance:								
Treatment vs. control	NS	NS	***	NS	NS	**	***	NS
Fertilizer vs. biosolids	*	***	***	***	NS	***	NS	***
Application rate	NS	NS	***	NS	NS	NS	***	NS
Year	***	***	***	NS	***	***	**	NS
Year × treatment	NS	*	**	NS	NS	NS	*	NS
Year × form of K	NS	NS	NS	NS	**	**	*	NS

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

Fig. 4. Calculated mean annual P balance (inputs from fertilizer or biosolids – outputs in grain and straw) plotted against mean soil Olsen P at Antrim. $y = 7.1479x - 62.1131$; $r^2 = 0.991$, $P < 0.001$. Diamond, control; squares, fertilizer; triangles, biosolids.

straw yields at both sites changed significantly from year to year, but there was no consistent trend of increasing or decreasing yield over the 7-yr study period.

Table 3 shows the grain and straw concentrations and offtakes of four major nutrients. Concentrations of N in grain and straw often differed between biosolid and fertilizer treatments, but they were not consistently higher or lower in either of these treatments. Concentrations of other nutrients tended to be higher in the biosolid treatments. Concentrations of most elements were higher in grain than straw, but K showed the opposite trend.

Values for soil pH, Olsen P, and exchangeable K in February 1992 (before the start of the experiment) and February 1999 (after seven annual crops) are shown in Table 4. The most marked effects of the biosolids were the liming action and the increases in the soil Olsen P and exchangeable K status with an increasing annual application rate. The linear contrasts for Olsen P and exchangeable K were significant at Antrim, which may have been due to the higher application rate and high K status of the biosolids at this site. At Hillsborough, the linear contrasts for soil pH and exchangeable K were significant.

The nutrient status of the barley shoots at the tillering stage allows for comparison among the nutrient-supplying capacities of the different treatments (Table 5). The most consistent effects were the higher concentrations of S in the shoots receiving biosolids at both sites (with the exception of the 1994 crop at Antrim) and the higher concentrations of P in the shoots receiving biosolids at Hillsborough. Shoot Mn concentrations tended to be lower in the biosolid treatments in later years, especially at Hillsborough, but were seldom below 10 mg kg⁻¹ (data not presented). The observation of higher shoot S concentrations in the biosolid treatments is supported by an analysis of water-soluble S in the soil samples collected in February 1998 (Table 6). Increasing the application rate of the alkaline biosolids led to a dramatic increase in the plant-available S in both soils.

The mean annual P balance at the Antrim site is shown in Fig. 4 plotted against the mean soil Olsen P over the 7 yr of the study. The P balance was calculated by subtracting the total (grain + straw) P offtake from total P application rate for each treatment in the experiment. The resulting regression line indicates that a soil Olsen P of 9 mg L⁻¹ should be maintained in basaltic clay soils to achieve a balance between inputs and outputs over the period of study. A similar balance study for K at the Hillsborough site (Fig. 5) indicates that soil exchangeable K should be maintained at 111 mg L⁻¹ in Silurian shale sandy clay soils.

DISCUSSION

The Antrim soil had a low Olsen P status before the experiment (8 mg L⁻¹) and would have been categorized as Index 0 (deficient in P) under the U.K. fertilizer recommendation system (MAFF, 1994). The Hillsborough soil had a K Index of 1 (low in K) with 116 mg L⁻¹. The two sites were selected on this basis so that

Table 4. Soil pH, Olsen P, and exchangeable K before the experiments and after seven consecutive annual barley crops.

Date	Antrim: Basaltic clay				Hillsborough: Shale sandy loam			
Feb	Treatment	pH	P	K	Treatment	pH	P	K
	kg ha ⁻¹ year ⁻¹	in H ₂ O	— mg L ⁻¹ —		kg ha ⁻¹ year ⁻¹	in H ₂ O	— mg L ⁻¹ —	
1992	None	5.9†	8.0	160	None	6.2‡	42.0	116
1999	0 (Control)	6.8	6.0	143	0 (Control)	6.5	29.5	88
	17 Fertilizer P	6.7	8.8	198	42 kg Fertilizer K	6.8	31.0	154
	35 Fertilizer P	6.8	13.0	208	83 kg Fertilizer K	6.8	31.0	168
	52 Fertilizer P	6.8	16.8	182	124 kg Fertilizer K	6.6	32.5	188
	70 Fertilizer P	7.0	28.5	207	166 kg Fertilizer K	6.5	30.2	193
	38 Biosolid P	7.8	17.5	413	80 kg Biosolid K	7.2	35.0	138
	75 Biosolid P	7.9	22.5	650	160 kg Biosolid K	7.5	37.5	170
	112 Biosolid P	7.9	33.5	829	240 kg Biosolid K	7.6	37.0	184
	150 Biosolid P	8.0	32.3	986	320 kg Biosolid K	7.8	38.5	252
Significance in 1999 (ANOVA) of:					Significance in 1999 of:			
Treatment		***	***	***	Treatment		*	***
P source (fertilizer vs. Agri-Soil)		***	***	***	K source		***	NS
P application rate		NS	***	***	K application rate		NS	***
P source × rate		NS	*	***	K source × rate		NS	NS

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† 3 Mg ground limestone ha⁻¹ was applied before the first crop in 1992.

‡ 2 Mg ground limestone was applied before the first crop in 1992.

yield-response curves applied to P or K could be derived. However, basaltic till soils such as the one at Antrim have high cation exchange capacities, high levels of exchangeable Ca and Mg, and abundant sesquioxides of Fe and Al derived from ferro-magnesian minerals (Cruickshank, 1997, p. 19). These soils often have high total P concentrations, but not all of the P associated with these soil constituents may be readily extracted by the Olsen reagent. As a result, the Olsen P method may tend to underestimate plant-available P in this soil type. The grain yield-response curves (Fig. 2) indicate that biosolid P may have been more available to the crop than fertilizer P over the 7 yr of the experiment. The

K response curves (Fig. 3) indicate that the availability of biosolid K was equal to that of fertilizer K.

The grain and straw yields and the grain-quality results show that the alkaline biosolids performed well compared with the inorganic fertilizers. It might be suggested that this was due to an improvement in the soil condition by the supply of additional C from the biosolids. However, this is unlikely to be an important factor because the Hillsborough soil has a relatively high organic C content for a temperate mineral soil (24 g kg⁻¹ in the top 15 cm), and the Antrim clay would be classified by the Ministry of Agriculture, Fisheries, and Food (1994) as an organic soil. A more likely explanation is that the high soil pH maintained by the sludge product may have contributed to the yield effect, possibly together with the alleviation of S deficiency. These two factors may have interacted with plant growth. Murphy

Table 5. Concentration of N, P, K, and S in the shoots at the tillering stage of the seven annual crops at both sites.

Date	Treatment	Antrim: Basaltic clay				Hillsborough: Sandy loam			
		N	P	K	S	N	P	K	S
		g kg ⁻¹							
1992	Fertilizer	35.2	2.19	29.8	2.48	24.2	1.92	32.1	1.60
	Biosolids	39.3	2.16	45.9	3.50	23.1	2.04	29.9	2.24
	Significance	**	NS	***	***	NS	*	*	***
1993	Fertilizer	27.8	3.23	29.5	2.96	22.4	2.48	35.4	1.88
	Biosolids	25.0	3.43	40.8	3.81	25.6	2.90	38.7	2.76
	Significance	NS	NS	***	**	*	***	**	***
1994	Fertilizer	48.3	3.68	40.5	3.80	44.2	3.51	45.2	3.96
	Biosolids	35.1	3.58	44.1	3.91	40.3	3.57	43.4	4.99
	Significance	***	NS	NS	NS	**	NS	NS	***
1995	Fertilizer	36.8	3.57	36.9	4.20	30.9	3.71	41.1	3.30
	Biosolids	37.6	3.82	53.5	4.82	33.8	4.28	50.0	5.87
	Significance	NS	**	***	***	**	***	***	***
1996	Fertilizer	27.6	3.07	29.5	3.36	19.7	2.64	30.0	2.07
	Biosolids	25.8	3.29	39.0	4.54	25.1	3.56	39.4	3.85
	Significance	NS	NS	***	***	NS	***	***	***
1997	Fertilizer	35.5	2.70	29.7	3.06	25.4	2.54	33.2	2.01
	Biosolids	28.7	3.09	32.1	3.63	25.0	3.28	37.3	3.64
	Significance	***	***	NS	***	NS	***	**	***
1998	Fertilizer	33.1	2.50	32.1	2.82	37.3	3.44	45.3	2.97
	Biosolids	22.1	2.84	33.3	3.22	36.5	4.00	48.1	5.10
	Significance	***	**	NS	***	NS	***	NS	***

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

Table 6. Water-extractable S in the two soils in February 1998 after six consecutive crops.

Antrim: basaltic clay		Hillsborough: shale sandy clay	
Treatment	S	Treatment	S
kg ha ⁻¹ year ⁻¹	mg L ⁻¹	kg ha ⁻¹ year ⁻¹	mg L ⁻¹
0 (Control)	16.4	0 (Control)	4.8
17 fertilizer P	13.7	42 kg fertilizer K	5.0
35 fertilizer P	16.5	83 kg fertilizer K	5.4
52 fertilizer P	13.7	124 kg fertilizer K	5.0
70 fertilizer P	15.0	166 kg fertilizer K	4.5
Mg ha ⁻¹ year ⁻¹		Mg ha ⁻¹ year ⁻¹	
17 biosolids DM	27.1	4 biosolids DM	6.9
34 biosolids DM	60.9	8 biosolids DM	10.0
51 biosolids DM	84.3	12 biosolids DM	12.9
68 biosolids DM	122.3	16 biosolids DM	19.8
Significance of:		Significance of:	
Treatment	*	Treatment	***
P source (fertilizer vs. biosolids)	***	K source (fertilizer vs. biosolids)	***
P application rate	***	K application rate	***
P source × rate	***	K source × rate	***

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

Fig. 5. Calculated mean annual K balance (inputs from fertilizer or biosolids - outputs in grain and straw) plotted against mean soil exchangeable K at Hillsborough. $y = 2.8154x - 307.7504$; $r^2 = 0.968$, $P < 0.001$. Diamond, control; squares, fertilizer; triangles, biosolids.

(1990) described the low atmospheric inputs of S to soils in Ireland and reported responsiveness of crops to S in Irish sandy soils with less than 30 g kg⁻¹ organic C. Sulfur in the alkaline biosolids is derived not only from the sewage sludge, but also from the cement kiln dust, which typically contains 50 g kg⁻¹ S (Love, 1990). The possibility of S deficiency was not considered when the experiments were designed; therefore, S was not routinely analyzed in the batches of biosolids used each year, and N, P, and K were the only major plant nutrients whose inputs were experimentally controlled. The higher shoot S concentrations at the tillering stage in plots receiving biosolids and the marked increase in soil-available S after six consecutive crops indicate that improved S nutrition may have contributed to the performance of the biosolids. However, S may not be the only nutrient involved in the yield response to biosolids. The mean offtakes of P and K in grain and straw were all higher in the biosolid treatments than in the fertilized plots. Although alkaline biosolids do not have high N concentrations, partly due to NH₃ volatilization during the mixing of the biosolids with the cement kiln dust and during the exothermic stage of composting, the liming effect may have stimulated the mineralization of soil organic N, especially in the organic basaltic clay. This effect has been reported in the forest soils to which alkaline biosolids were applied (Luo and Christie, 1995).

The fate of trace metals derived from the biosolids will be the subject of a separate paper, but it is interesting to note that both Zn and Cu were well below their toxic thresholds of 200 and 20 mg kg⁻¹, respectively (Bailey, 1993), in the shoots at the tillering stage. Concentrations in the grain and straw were similar to those in the control and fertilizer treatments. These results were obtained despite the use of excessive biosolid application rates, especially at the Antrim site. There was some evidence of a decline in Mn availability, particularly in the later years of the study, but few of the shoot concentrations fell below the deficiency threshold of 10 mg L⁻¹ (Bailey, 1993). Manganese deficiency is the most widespread nutrient deficiency in Northern Ireland cereals, but it is usually associated with adverse weather conditions and coarse sandy soils (Dickson and Christie, 1985). Thus, care would need to be taken to avoid Mn deficiency when applying alkaline biosolids to these soil

types for cereal production. The deficiency could be corrected at the tillering stage by foliar application of Mn (Brown et al., 1997).

The P and K balances help explain the absence of grain yield-response curves to increasing P or K inputs in these experiments. Although the Antrim soil would be classed as deficient in P and the Hillsborough soil as low in K, the initial Olsen P at Antrim was only 1 mg L⁻¹ below the indicated soil level for P balance, and the exchangeable K at Hillsborough was actually 5 mg kg⁻¹ above the calculated soil K level for K balance. This is especially important for P because agronomically small annual losses of P from agricultural soils can eventually lead to environmentally damaging enrichment and eutrophication of rivers and lakes. The U.K. fertilizer recommendation system categorizes soil Olsen P into index values as follows:

Index 0	0–9 mg P l ⁻¹	Deficient
Index 1	10–15 mg P l ⁻¹	Low
Index 2	16–25 mg P l ⁻¹	Adequate

Samples of farmers' soils are analyzed for Olsen P, and the result of each soil test is placed in the appropriate index. A recommendation is then made that is designed to adjust the soil-available P to the target index, which is Index 2. It would not be possible to make fine adjustments to the system based on two field experiments on two soil types. However, the present study indicates that the system could be adjusted by changing the target range of Olsen P to Index 1, instead of Index 2. This could make a convenient and useful contribution to reducing nonpoint-source P pollution from agricultural soils. Although P in organic wastes is usually regarded as having an average of 50% availability to the next crop after application (Simpson, 1986, p. 90–99), our P balance study indicates that availability is similar to that of P in inorganic fertilizer over a 7-yr period (Fig. 4). This agrees with the study of McLaughlin and Champion (1987) who conducted a pot-experiment study on the plant availability of sewage sludge P applied to two sesquioxide soils using monocalcium phosphate as a standard. They found that the relative efficiency of sludge P reached 90% in one of the soils and over 100% in the other with time, and the sludge appeared to act as a slow-release P fertilizer. In the present study, it was very difficult to find a field with a soil Olsen P value as low as Index 0 for the P experiment, and the Olsen test may have also underestimated the available P in the basaltic soil as discussed above. This illustrates the widespread accumulation of P in intensively managed agricultural soils over the last 50 yr and indicates that many soils may have substantial P reserves for crop growth. Such soils may require very modest, routine P application rates to maintain optimum crop yields while minimizing losses of P to surface waters.

CONCLUSIONS

The results of this study indicate that P and K in alkaline biosolids have similar plant availability to P and K in inorganic fertilizer. Relatively low application

rates (up to about 5 Mg ha⁻¹) of alkaline biosolids could be used for several years to maintain crop production, even on soils with small reserves of available P. This might supply up to about 150 kg S ha⁻¹. Nitrogen and K could be supplemented using inorganic fertilizers to achieve optimum yields. The alkaline biosolids could replace ground limestone for control of soil pH in acidic soils when used regularly at low application rates. Each batch of biosolids would need to be analyzed before use to determine the correct application rate, and soil analysis would enable the monitoring of trace metal accumulation in the soil. Barley grows well at relatively high soil pH, but other cereal crops may be more sensitive to increases in soil pH from repeated use of alkaline biosolids. Our results indicate that alkaline biosolids could be useful as a combined seedbed fertilizer and liming material for cereal crops grown in acidic soils under carefully controlled conditions.

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