Meat and bone meal and biosolids as slow-release phosphorus fertilizers

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Biosolids and meat and bone meal (MBM) are commonly used as fertilizers in agriculture, often at application rates where total phosphorus (P) far exceeds the annual demand. In a pot experiment, three biosolids and two types of MBM were tested at two commonly used application rates. Their contributions to P uptake in ryegrass (second and third season) were compared with annual mineral P fertilization. The soil was analysed for extractable P (P_{AL} and P_{Olsen}). Only soil amended with digested, limed biosolids provided a P uptake in ryegrass the third season comparable to annual NPK fertilization. Bone-rich MBM had considerable contributions to third season P uptake in soil with pH < 6. The product application rates did not influence P uptake significantly for any of the products. P_{Olsen} was found suitable to describe residual effects on soil P solubility, whereas the P_{AL}-method was not applicable for MBM fertilized soils.

Key words: Availability - P_{AL} - P_{Olsen} - ryegrass- organic fertilizers - sewage sludge

Introduction

Recovery and reuse of phosphorus (P) from waste and wastewater is gaining attention as a measure to meet and secure future P demand in food production (Ashley et al. 2011, Cordell et al. 2011). Biosolids and meat and bone meal (MBM) are important products in anthropogenic P systems, as they contain considerable quantities of P from food processing and consumption (Boen and Grønlund 2008, Ott and Rechtberger 2012). The bone fraction in slaughtering waste is especially rich in calcium phosphates. According to Antikainen et al. (2005) more than 60 % of the P entering domestic food consumption in Finland ended up in sewage sludge, which can be processed into biosolids. These waste- and wastewater-based products (WBPs) can potentially supply P to food production and create circular anthropogenic P flows, which could reduce or complement the current demand for P from rock phosphates.

Biosolids and MBM are well established input materials in agriculture. In 2010, 54% of Norwegian biosolids were applied in agriculture (Statistics Norway 2012). The use of MBM as a fertilizer has expanded since 2000 and in 2010; 70% of low risk MBM in Norway was used as organic fertilizer (Norsk Protein AS, personal communication 2012). For farmers, low-cost access to nutrients, organic matter and occasionally lime are regarded as the most important benefits of biosolids application to agricultural land (Refsgaard et al. 2004), which can explain why application rates of biosolids are commonly decided by criteria such as organic matter demand, N fertilizer effect or legal limitations. As a consequence, P applications to soil can be very high (Maguire et al. 2000, Krogstad et al. 2005). MBM has also proven to be an efficient N fertilizer because of its rapid mineralization in the soil (Jeng et al. 2004, Delin and Engstrom 2010). Due to low N:P ratio, P accumulation in soil has also been a concern when MBM is used to cover N demand (Ylivainio et al. 2008, Chen et al. 2011).

In Western Europe, soils usually have good P status (Csathó and Radimsky 2010). There is no good agronomic reason for increasing the P content in well-fertilized soils and indeed further accumulation of P in the soil can be an environmental concern with regard to eutrophication of surface waters (Sharpley et al. 1994, Bechmann and Deelstra 2005). In many countries the general advice for soils with a moderate soil P status is a non-accumulation principle, where P supplied in fertilizer should balance P taken out by the crops (Knudsen 2008, Krogstad et al. 2008). For biosolids, MBM and other recycled fertilizer products not explicitly designed to optimize NPK ratio or P availability, it is a great challenge to use these products in such a way that their potential as P fertilizer is utilized and their contribution to long-term P accumulation in soil is minimized. For products with a slow-release P fertilizer effect in particular, their long-term effect on soluble P in the soil and the response in P uptake must be understood in order to provide good P fertilizer recommendations.

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The P fertilizer effects of biosolids have been found to vary over a wide range (O'Connor et al. 2004, Krogstad et al. 2005). The availability is reported to be similar to that of triple superphosphate for biosolids produced from biological P removal, but is lower when chemical precipitation processes are involved. MBM have been reported to have a moderate first season effect, but also a considerable residual effect in the second and partly third seasons (Jeng et al. 2006, Ylivainio et al. 2008). In general, long-term experiments on the P fertilizer effects of biosolids and MBM have been few. However, as application of these products in agriculture can result in considerable P surpluses in the soil after the first season, it is necessary to understand how the residual P can supply P to the plants in the following years. The objectives of this study were therefore to evaluate three chemically precipitated biosolids and two types of meat and bone meal with regard to: 1) their effects as slow-release P fertilizers; 2) their second and third season effects on extractable soil P (P_{Olsen} and P_{AL}); and 3) the three-year P balance in different soils.

Materials and methods

The pot experiment

A 3-year pot experiment with perennial ryegrass (*Lolium perenne*, cv. 'Napoleon') was conducted in 5.6 l pots (top diameter 20.5 cm, height 19 cm). Three types of biosolids (dBS Lime, BA Lime and dBS) and two types of meat and bone meal (MBMm and MBMb) were applied in spring of the first season and mixed into the upper 5 cm of the soil. The biosolids were all precipitated with Al and/or Fe-salts, but otherwise had different treatment histories: For dBS Lime, the sludge was anaerobically digested (d=digested) before lime application ($Ca(OH)_2$) in the dewatering process; the BS Lime sludge was stabilized and sanitized by CaO addition; and dBS was digested, but no lime was applied. The two MBM products were produced at different processing plants (Norsk Protein Hamar and Norsk Protein Mosvik), one of which had a dominance of slaughter waste from chickens. Its product (MBMm, m=meat) had a higher content of meat or soft parts than that of the other plant, which was more dominated by cattle bones (MBMb, b=bones). Chemical properties of the products are shown in Table 1.

The pot experiment was carried out using topsoil (0–25 cm) with different soil textures taken from two agricultural fields (Table 2). One of the soils, a silt loam, had a moderate content of plant-available P (P_{AL}; Krogstad et al. 2008). The other soil, a loam, had low P_{AL} content. The pots (triplicates per treatment) were placed in a completely randomized design under a large glass roof where they were protected from precipitation and snow cover, but were otherwise exposed to the outdoor climate. Average temperature during the summer months (June–August) was 15.6, 15.3 and 15.3 ºC for the three consecutive years (UMB 2012). The pots were kept at a water content of 0.25–0.35 $m^3\,m^{-3}$ for the silt loam and 0.3–0.4 $m^3\,m^{-3}$ for the loam, which was estimated to represent a water potential between -10 and -100 kPa.

Table 1. Content of elements (% of dry matter) and pH in the three biosolids products (dBS, dBS Lime and BS Lime) and two meat and bone meal products (MBMb and MBMm) tested in the pot experiment.

	P (%)	C (%)	Ca (%)	N (%)	Fe (%)	pH
MBMb	4.8	39	13.8	7.4	n.d.	6.3
MBMm	2.6	48	4.8	9.1	n.d.	n.d.
dBS	1.5	21	1.2	2.5	19.2	8
dBS Lime	1.9	18	15	2.1	3	7.9
BS Lime	0.8	18	20	1.9	4.5	>11

MBMb –meat and bone meal dominated by bones, MBMm –meat and bone meal dominated by meat, dBS – digested biosolids, dBS Lime – digested, limed biosolids, BS Lime – limed biosolids

Application rates for biosolids and MBM were based on 'typical' application rates for these products in agriculture. By choosing this approach, it was possible to study the slow-release P fertilizers effects of these treatments in comparison with annual NPK and NK fertilization. However, the total P loads applied by the different treatment highly dependent on the P concentrations in the different products (Table 3). The biosolids were tested at two application levels (20 tons and 10 tons dry matter (dm) ha^{-1}). The meat- and bone meal products were applied at two different rates, the highest (1/1 N) simulating a nitrogen (N) -based fertilization strategy (240 kg available N ha^{-1} in the first season). For the lower application rate (1/2 N), half the N (120 kg available N ha^{-1}) was supplied by MBM in the first season and half by NK fertilizer. In addition to the pots fertilized with biosolids or MBM, an additional set of pots received NPK (NPK 18-3-15) and NK (NK 22-11) fertilizer at a rate of 240 kg N ha^{-1} each year. Unfertilized control pots were also included. The NPK fertilized soil received 40 kg P ha^{-1} annually, which was assumed to roughly balance P uptake by plants.

Table 2. Description of the two soils used in the experiment.

	Silt loam	Loam
Soil texture		
sand (%)	20	50
silt (%)	53	30
clay (%)	27	20
pH	5.8	6.7
Olsen-extractable P (mg kg^{-1} dm)	43	21
Water-soluble P (mg kg^{-1} dm)	1.7	1.2
AL-extractable nutrients (mg kg^{-1} dm)		
P	63	28
K	172	69
Mg	182	142
Ca	1050	2680

dm – dry matter

Table 3. Rate of P application and soil P balance (P applied – P uptake) the first, second and third autumn after application of three different biosolids (dBS Lime, BS Lime and dBS) and two different meat and bone meals (MBMb and MBMm). The biosolids were applied at two different application rates (10 and 20 tons dm ha^{-1} as a one-time addition). The meat and bone meals were applied as 240 kg N ha^{-1} (1/1 N) or 120 kg N ha^{-1} (1/2 N). NPK- and NK-fertilized soils were also included.

		P applied (kg ha^{-1})				P balance (kg ha^{-1})					
						Silt loam			Loam		
	Year	1	2	3	All	1	2	3	1	2	3
NPK		40	40	40	*120*	18	14	6	24	32	38
NK						-21	-58	-89	-12	-32	-47
	tons dm ha^{-1}										
dBS Lime	20	380			*380*	348	297	251	359	319	280
	10	190			*190*	164	117	75	170	136	107
BS Lime	20	160			*160*	129	79	39	141	107	76
	10	80			*80*	55	10	-27	67	34	9
dBS	20	300			*300*	277	238	204	285	256	232
	10	150			*150*	129	90	55	135	109	88
	240 kg N ha^{-1} by										
MBMb	1/1 N	154			*154*	123	80	40	141	114	94
	1/2 N	77			*77*	51	12	-28	62	36	16
MBMm	1/1 N	69			*69*	41	-2	-39	54	27	7
	1/2 N	34			*34*	11	-31	-66	22	-3	-20

MBMb –meat and bone meal dominated by bones, MBMm –meat and bone meal dominated by meat, dBS – digested biosolids, dBS Lime – digested, limed biosolids, BS Lime – limed biosolids, dm – dry matter

All treatments (except the unfertilized controls) were planned to have similar access to plant-available N (240 kg available N ha^{-1}) each season. The two MBM products were assumed to have a first season N availability of 80% (Jeng et al. 2004). As first season N mineralization from biosolids was unknown, biosolids-amended soils received 240 kg N ha^{-1} as NK fertilizer in the first year. In the second and third spring, all biosolids and MBM treatments received 240 kg N ha^{-1} as NK 22-11. Before application, the upper 5 cm of the soil was taken out and mixed with the fertilizer. After replacement of the soil, the pots were resown with ryegrass. The grass was cut three times each season. Annual differences in P availability to ryegrass were better reflected in P uptake (kg ha^{-1}) than in yield (kg dm ha^{-1}, annual yield data not presented). Annual differences in second and third season P availability are therefore mainly discussed on the basis of P uptake. The biosolids had a considerable N fertilizer effect, especially in the first season. N contributions from the biosolids resulted in higher biomass production, especially in treatments amended with digested biosolids (dBS Lime and dBS) . As P uptake was highly influenced by the biomass production, this complicated the interpretation of first season P uptake results. The first season data on yield and P uptake are therefore not presented separately in this paper. The unfertilized control had low biomass production due to N deficiency (52 % of NPK in the silt loam and 46 % of NPK in the loam for all three seasons). Due to the N driven yield differences, P uptake in the unfertilized control soils will therefore not be further compared to the N-fertilized treatments.

Chemical analyses

Total nitrogen in WBPs was determined in moist samples by a modified Kjeldahl procedure (EN 13654-1 2001). This method also includes nitrate-N and nitrite-N in the Kjeldahl determination, by an initial reduction to the amino form with thiosulphate. Total organic carbon (C) in WBPs was determined by combustion after washing with a 2 M HCl solution. Total phosphorus (P), calcium (Ca) and iron (Fe) in WBPs were determined by ICP-OES after nitric acid dissolution at high temperature and high pressure. pH was measured in raw materials with a WBP to water ratio of 1:95 (w/w). Water-extractable P (WEP) in WBPs was measured colorimetrically by the molybdate blue method (Murphy & Riley 1962) in filtered samples (0.45 µm) after 22 h extraction with distilled water (2:40, w/v).

The soil was sampled before the experiment and, in addition, soil samples were taken with a small soil core sampler each autumn. The soil samples were dried at 40 °C and sieved (2 mm). The pH in soil samples was determined in dried samples with a soil:water ratio of 1:2.5 (v/v). Loss of weight on ignition (LOI) was determined after ignition at 550 °C for 4 hours. Readily available P was determined 1) after 1.5 h extraction (2:40; w/v) in a buffered solution (pH 3.75) with 0.1 M ammonium lactate and 0.4 M acetic acid (P_{AL}; Egnér et al. 1960) and by 2) 0.5 h extraction (1.5:30; w/v) with 0.5 M $NaHCO_3$ solution buffered to 8.5 (P_{Olsen}; Kuo 1996). The P content was determined colorimetrically by the molybdate blue method (Murphy and Riley 1962). The AL method is the standard soil P test for agricultural soils in Norway and Sweden. Potassium (K), magnesium (Mg) and Ca was also measured by the AL method in the original soils. The P content in dried (40 ºC) ryegrass samples was measured by ICP-OES after nitric acid dissolution at high temperature and high pressure. Biomass production (above ground) was measured for each pot. P concentration in grass was analysed for one pooled sample per treatment. Soil samples were analysed for each pot.

Calculations and statistical analysis

P uptake results are presented as kg ha^{-1}, conversion to pot scale were done on the basis of surface area of the pots. The soil cylinder was approximately 15 cm high. Yield, P uptake and extractable P (P_{AL} and P_{Olsen}) were analysed by one-way ANOVA models for each soil type. Tukey's test was applied to determine significant differences in P uptake between treatment means. Tukey's test was also used to analyze differences in extractable P. Orthogonal contrasts were used to analyse yield differences between NPK-fertilized soil and soils fertilized with biosolids (dBS Lime, BS Lime and dBS), meat and bone meal (MBMb and MBMm) and NK-fertilizer (Table 6). A two-way ANOVA model was used to analyse whether the different products were utilized differently in the two soil types when variation caused by application rate was blocked. The 0.05 probability value was used to determine significant differences where no other significance level is stated. Correlation coefficients always refer to simple linear regression models. t-tests were used to test the significance of the regression slopes (α=0.05). t-test for different slopes was used to test differences between biosolids and MBM for P uptake as a response to P_{AL} and P_{Olsen}.

Results and discussion

Second and third season P fertilizer effects of biosolids and MBM

The P uptake in ryegrass in treatments receiving limed biosolids (dBS Lime and BS Lime) was not significantly different from that in NPK-fertilized soils in the second season (Table 4). A considerable third season P fertilizer effect of limed biosolids was also observed. However, P uptake from soils fertilized with limed biosolids was lower in the third season compared with the second season, indicating a decreasing ability to supply P to the plants. Both the digested biosolids (dBS) and the MBMs contributed to higher P uptake than the NK treatment in the second season, but the Tukey's test did not separate second season effects very well. In the third season, the bone-rich MBMb had significantly higher contributions to P uptake than the NK treatment. However, the P uptake was still significantly lower than from the NPK fertilized soils. The results confirm that there were differences between the biosolids and MBM treatments in their ability to supply P to the plants in the second and third season after application. However, the product application rates influenced the second and third year P uptake significantly only where limed biosolids were applied to the loam soil. Otherwise the differences were small. The results suggest that there were only small benefits of applying the highest rate on the long-term contribution to P uptake in plants.

The limed biosolids (dBS Lime and BS Lime) supplied more P to plants than dBS in the second and third season. Because of the lime additions, dBS Lime and BS Lime had high Ca concentrations (Table 1). dBS had low Ca content, but a very high Fe content. The differences in P availability between the biosolids therefore support previous findings that biosolids with high Fe content have low availability to plants, whereas biosolids precipitated with Fe- or Al salts have a higher content of plant-available P when lime is added during sludge treatment (Frossard et al. 1996, Maguire et al. 2001, O'Connor et al. 2004, Krogstad et al. 2008). Lime stabilization of Fe-precipitated sludge has been shown to increase the content of Ca-phosphates, predominantly hydroxyapatite-P and other Ca-phosphates with low solubility (Frossard et al. 1996, Sui et al. 1999, Shober et al. 2006). However, because of the liming effect of dBS Lime and BS Lime, the soil pH was raised to near neutral (6.5–7.0 in the silt loam and 7.3–7.6 in the loam). At these pH values, sparingly soluble P forms such as hydroxyapatite can be expected to have a low solubility (Hinsinger 2001). The differences between dBS and the limed biosolids (dBS Lime and BS Lime) can be assumed to be a combination of lower metal content and possibly presence of Ca-bound P. However, the mechanisms leading to higher P availability in limed biosolids are not fully understood.

Table 4. Mean P uptake (kg ha^{-1}) in ryegrass in the second and third season after application of three different biosolids (dBS Lime, BS Lime and dBS) and two different meat and bone meals (MBMb and MBMm). The biosolids were applied at two different application rates (10 and 20 tons dm ha^{-1}). The meat and bone meals were applied as 240 kg N ha^{-1} (1/1 N) or 120 kg N ha^{-1} (1/2 N). Tukey's test (T) compares annual P uptake for the different treatments, the two soil types were analysed separately (one-way ANOVA-model).

		P uptake (kg ha^{-1})							
		Silt loam				Loam			
		Year 2		Year 3		Year 2		Year 3	
		2	T	3	T	2	T	3	T
NPK		45	bcd	47	a	32	b	35	b
NK		37	e	31	e	19	f	15	h
	tons dm ha^{-1}								
dBS Lime	20	50	a	46	a	40	a	39	a
	10	47	abc	42	ab	34	b	29	c
BS Lime	20	50	ab	40	bc	35	b	31	c
	10	46	abc	36	bcde	33	b	25	d
dBS	20	39	de	34	e	29	c	23	de
	10	39	de	35	cde	26	de	21	ef
	240 kg N ha^{-1} by								
MBMb	1/1 N	42	cde	40	bc	27	cde	21	f
	1/2 N	40	cde	40	bcd	26	cde	20	f
MBMm	1/1 N	43	cd	36	cde	27	cd	19	fg
	1/2 N	42	de	35	de	24	e	18	g

MBMb –meat and bone meal dominated by bones, MBMm –meat and bone meal dominated by meat, dBS – digested biosolids, dBS Lime – digested, limed biosolids, BS Lime – limed biosolids, dm – dry matter

The P uptake (kg ha^{-1}) was generally lower in the loam than in the silt loam. Lower P_{AL} values in the original soil and P-limited yield (see below) are considered the most important factors for lower P uptake in the loam. The MBMs supplied the plants better in the silt loam (Table 4). Significant interaction effects between product and soil type were confirmed in a two-way ANOVA model. As seen in Table 5, MBM application elevated P_{Olsen} more in the silt loam than in the loam, especially in the first autumn, suggesting higher residual fertilizer effect in the silt loam. The solubility of hydroxyapatite, which is the main constituent of MBM-P, is highly dependent on pH (Hinsinger 2001). The MBM-fertilized silt loam had pH ranging from 5.6–5.9, whereas pH ranged from 6.4–6.8 in the MBM-fertilized loam. The differences in soil pH were probably the main reason for the differences in soil P solubility and P uptake between the two soil types.

P_{AL} as a standard soil P test in soils fertilized with biosolids and MBM

The long-term effects of WBPs will depend on their effects on P solubility in the soil, i.e. how they contribute to P release into the soil solution. dBS Lime application resulted in the highest P_{Olsen} values in the soil, significantly higher than dBS in the silt loam (third autumn) and loam (first and third autumn, Table 5).

Table 5. P_{Olsen} and P_{AL} in soil sampled in autumn in the first and third growing season after application of three different biosolids (dBS Lime, BS Lime and dBS) and two different meat and bone meals (MBMb and MBMm). The biosolids were applied at two different application rates (10 and 20 tons dm ha^{-1} as a one-time addition). The meat and bone meals were applied as 240 kg N ha^{-1} (1/1 N) or 120 kg N ha^{-1} (1/2 N). NPK- and NK-fertilized soils were also included. T refers to Tukey's test for differences between means, soil types and seasons are analysed separately (one-way ANOVA model). P_{AL} results for MBM-fertilized treatments are not included in the Tukey's test, as the AL method proved to have a low correlation to P uptake in plants.

		P_{Olsen} (mg kg^{-1} dm)								P_{AL} (mg kg^{-1} dm)							
		Silt loam				Loam				Silt loam				Loam			
	Year	1	T	3	T	1	T	3	T	1	T	3	T	1	T	3	T
NPK		40	abc	39	a	11	cd	21	c	70	de	65	de	33	bcd	53	ab
NK		33	cd	28	d	9	d	9	d	50	e	38	e	19	d	18	c
	tons dm ha^{-1}																
dBS Lime	20	43	abc	34	a	30	a	34	a	106	a	82	a	125	a	94	a
	10	40	abc	34	abc	17	bc	20	b	84	bc	67	b	61	b	48	ab
BS Lime	20	37	abcd	38	ab	18	bc	20	b	84	bc	81	b	67	b	50	a
	10	31	d	31	cd	13	bcd	14	c	62	cd	52	bcd	46	cd	36	bc
dBS	20	33	cd	28	d	13	bcd	13	cd	74	bc	53	bc	58	bc	44	bc
	10	35	bcd	28	d	10	d	10	cd	61	d	44	cde	40	cd	29	c
	240 kg N ha^{-1} by																
MBMb	1/1 N	43	a	32	bcd	13	bcd	11	cd	179		124		183		83	
	1/2 N	41	ab	32	bcd	11	cd	12	cd	111		76		73		49	
MBMm	1/1 N	37	abcd	30	cd	10	d	10	cd	96		65		69		42	
	1/2 N	34	bcd	30	cd	9	d	9	d	67		53		42		25	

MBMb –meat and bone meal dominated by bones, MBMm –meat and bone meal dominated by meat, dBS – digested biosolids, dBS Lime – digested, limed biosolids, BS Lime – limed biosolids, dm – dry matter

The bone-rich MBM (MBMb) also raised P_{Olsen} in the silt loam in the second season. P_{Olsen} was significantly correlated to P uptake in ryegrass. P_{Olsen} explained 47% of the variation in third season P uptake in the silt loam and 92% in the loam (r^2 for simple linear regression). P_{Olsen} extraction therefore appears to be an acceptable method for describing the plant availability of P in soils fertilized with MBM and biosolids.

Soil P tests are used for planning the next year's fertilization and must therefore have a reasonable correlation to P uptake in the following year. In Norway, P_{AL} is the standard soil P test used for agricultural soils. This method generally extracts more P from agricultural soils than the P_{Olsen} method (Knudsen 2008, Krogstad et al. 2008). In the present study, MBM efficiently increased soil P_{AL}, but had limited effect on P uptake in plants (Fig. 1 A and B). For biosolids, there was a good correlation between P uptake and P_{AL}, as documented previously by Krogstad et al. (2005). There were significant differences in how P uptake responded to soil P_{AL} in biosolids-fertilized soils and MBM-fertilized soils (t-test of different slopes). The differences were more distinct in the loam than in the silt loam, but were significant in both soil types. With regard to P_{Olsen}, P uptake could be described with a common linear regression for biosolids-fertilized and MBM-fertilized soils (no significant difference between slopes) (Fig. 1C and D). The results document that P_{AL} overestimated the availability of P in MBM-fertilized soils, especially in cases where MBM application induced high elevation of the soil P_{AL} value. The same was suggested by Brod et al. (2012).

The overestimation was most likely caused by higher solubility of hydroxyapatite in the AL solution (buffered to pH 3.75) than in the soil (Hinsinger 2001, Warren et al. 2009). Similar conclusions have been drawn for the acid ammonium acetate extraction method (pH 4.65), which has similarities to the AL method (Ylivainio et al. 2008).

The pH values in the MBM-fertilized soils were almost one pH unit lower in the silt loam (pH 5.6–5.9) than the loam (pH 6.4–6.8), suggesting higher solubility of MBM-P in the silt loam. As described previously, MBM also supplied P better in the silt loam than in the loam. For MBM-fertilized soils, we expected the P_{AL} to be better correlated to P uptake in the silt loam than in the loam. However, the results demonstrated severe problems with interpretation of P_{AL} values in both soil types. As P_{AL} values overestimate the ability of the soil to supply P to the plants, use of P_{AL} values in fertilizer planning can underestimate the need for P fertilization in the years after application.

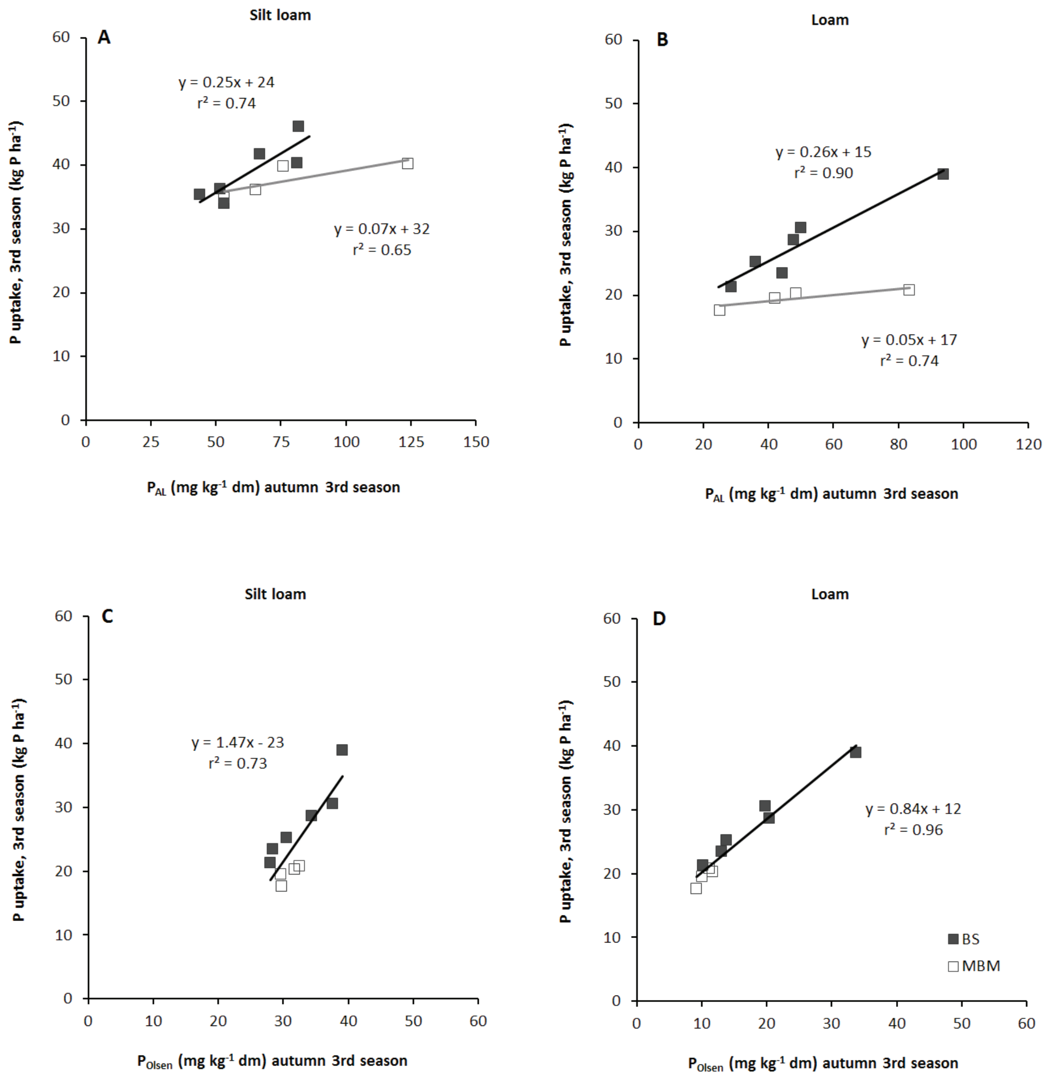

Fig. 1. Uptake of P (kg P ha^{-1}) in ryegrass in the third season in relation to soil P_{AL} (A and B) and P_{Olsen} (C and D) in the two soil types (silt loam and loam). Results are divided between treatments fertilized with biosolids (BS) and meat and bone meal (MBM). Linear regression lines describe the relationship between P_{AL} and P uptake (A and B) and P_{Olsen} and P uptake (C and D). For the P_{AL} method, separate regression lines are given for MBM-fertilized (grey) and biosolids-fertilized (black) soils. For the Olsen method, a common regression line (black) is given for MBM-fertilized and biosolids-fertilized soils. (dm – dry matter)

Seasonal variation in P uptake and yield

Compared with annual NPK fertilization, biosolids-fertilized and MBM-fertilized treatments had lower yield in early season (Fig. 2 and Table 6). The slow start was compensated for by higher yields later in the season, explaining why the annual yield differences were rather small. Low yield in early season was also accompanied by low P concentrations in the plants, suggesting that low yield in early season was caused by limited access to P. The range of variation in P concentration was 1.0–4.4 g kg^{-1} and the P concentrations were lower in the first cut than at later cuts. Mean P concentration in the first cut (all years) was 2.5 g kg^{-1} in the silt loam and 2.0 g kg^{-1} in the loam. In the third cut (all years), the mean P concentration was 3.3 in the silt loam and 2.2 in the loam. The lowest P concentrations, 2.0 mg kg^{-1} in silt loam and 1.3 mg kg^{-1} in the loam, were observed in the first cut in the third year, the occasion on which yield differences were also most distinct. The normal P concentration range in ryegrass is reported to be 3.5–5 mg kg^{-1} dm, whereas severe P deficiency has been observed at plant P concentrations < 1 mg kg^{-1} dm (Yli-Halla 1991, Bergmann 1993).

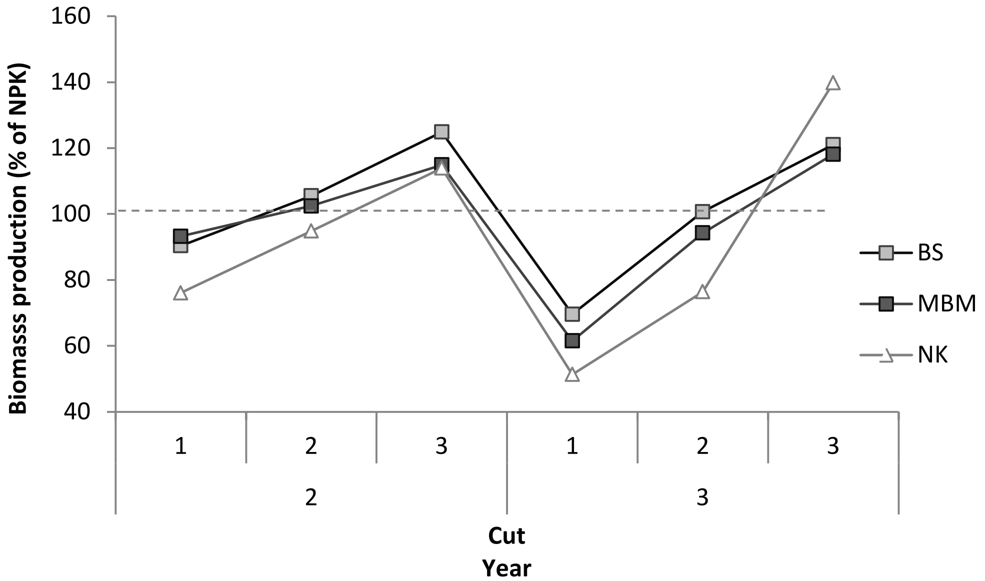

Fig. 2. Yield in individual cuts in the second and third season for loam soils fertilized with biosolids (BS), meat and bone meal (MBM) and NK fertilizer. The results are given for individual cuts (1-3) in the second and third season, as a per cent of yield obtained by annual NPK fertilization. Statistics are given in Table 6.

Table 6. Significance table for yield, comparing NPK fertilization with all biosolids treatments (BS), all meat and bone meal fertilized treatments (MBM) and NK fertilization (one-way ANOVA model) in individual cuts in the second and third season. The results are shown in Figure 2. Differences were analyzed by orthogonal contrasts for separate cuts in the second and third season. (↑) indicates higher yield than in the NPK-fertilized treatments and (↓) lower yield. One arrow indicates a significant difference at $p < 0.05$, two arrows a significant difference at $p < 0.01$. (ns) denotes no significant difference.

	Year 2			Year 3		
Cut	1	2	3	1	2	3
NK	↓↓	ns.	ns.	↓↓	↓↓	↑↑
BS	↓↓	ns.	↑↑	↓↓	ns.	↑↑
MBM	↓	ns.	↑	↓↓	↓	↑↑

An adequate P supply in the early stages of plant growth has been pointed out as important for optimum yield in many crops (Grant et al. 2001, Kristoffersen et al. 2005). An important problem for MBM and biosolids as long-term fertilizers is that they do not supply sufficient P in early season when the root system is small. However, this is apparently less limiting for ryegrass yield than for several other crops, as the ryegrass was able to compensate for P limited growth in early season by higher yields later in the season. Nitrogen mineralization can be a contributing factor to the relative increase in late-season yield, especially in biosolids-fertilized soils (Bøen and Haraldsen 2011). However, ryegrass was more sensitive to P deficiency in early season than late season. For treatments with low plant P concentrations (< 2 g kg^{-1} dm), there was a significant correlation between first cut yield and first cut P concentration in plants (Fig. 3 A; r^2=0.80), confirming that yield was restricted by low P supply to plants in early season. In the last cut, high yield was observed even at plant P concentrations of 1–2 mg kg^{-1} dm, suggesting that the ryegrass was less sensitive to P availability when the root system was established. The P uptake was highly correlated with plant P concentration < 2 g kg^{-1} dm in both early (r^2=0.56) and late season (r^2=0.67, Fig. 3 B).

The ability of ryegrass to compensate for P-restricted growth in early season has also been described by Ylivainio et al. (2008). They argued that the ability of ryegrass to utilize MBM is due to low external P requirements and a long growth period, and they suggest MBM as a storage P fertilizer for plants with these characteristics. Our results support their findings, and suggest that similar recommendations can be used for biosolids. It has also been argued that, because of their slow P release and the high P quantities applied to the soil, biosolids should not be regarded as an alternative to mineral P application. Instead, they are suggested to be more suitable for corrective P fertilization, for example in soils with low P status (Ottabong 1997). Limed biosolid products could be efficient for this purpose, as they increased the level of extractable P in the soil (P_{Olsen} and P_{AL}). The P_{AL} results also suggest a small contribution of dBS to the plant availability of P, as also previously documented in four-year field experiments (Øgaard and Bøen 2012).

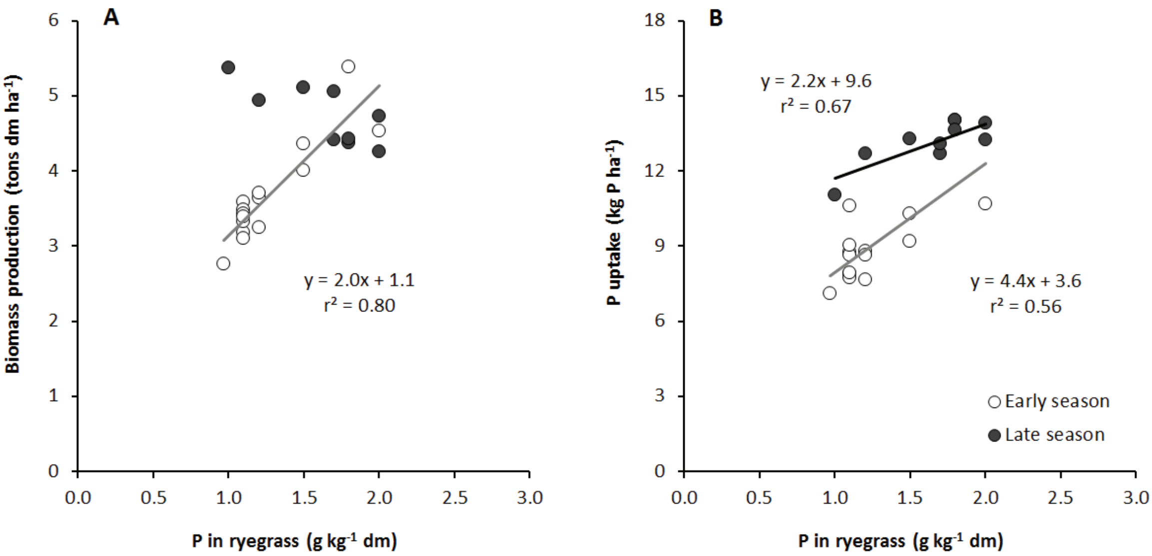

Fig. 3. Third season yield (A) and P uptake (B) in ryegrass when P concentrations in the plants were < 2 g kg^{-1} dm. The results are for the loam soil and is divided between early season (first cut) and late season (third cut). (dm – dry matter)

P balance in BS-fertilized and MBM-fertilized soils

After three years, the P balance in the soil was, not surprisingly, very much a reflection of the total P application (Table 3). The highest P surpluses were found where digested biosolids (dBS and dBS Lime) and bone-rich MBM (MBMb) had been applied. Soils amended with 20 tons dm ha^{-1} of dBS Lime and dBS had the highest P surpluses and also the highest P inputs. A 50% lower P input (10 tons dm ha^{-1}) resulted in 70 and 73% lower P surplus for the two products, respectively. Generally, the lower application rates would be preferable in order to reduce the P surpluses in the soil. A possible justification for higher application rates could be an ability to supply P over a longer period. The P_{AL} and P_{Olsen} values suggested slightly higher P solubility when 20 tons dm ha^{-1} was used compared with 10 tons dm ha^{-1}. However, the differences were small and do not indicate large differences between the two loads in their ability to supply P to plants in the years ahead. This raises two points. First, it appears that dBS and dBS Lime cannot be applied to the soil without accepting a certain long-term P surplus. Second, the benefit of of 20 tons dm ha^{-1} compared with 10 tons dm ha^{-1} on longer term P supply to plants appears marginal in comparison with the very high P surplus obtained in the soil with the higher application rate.

Annual application as P fertilizer or bi-annual application as N fertilizer has been suggested as a fertilization strategies for MBM (Jeng et al. 2006). Our results support their conclusion regarding the second season P fertilizer effect and also suggest a considerable third season effect for MBMb. As seen in Table 3, all MBM treatments resulted in a soil P surplus after the first growing season. Annual application to cover N supply (1/1 N or 1/2 N) would therefore accumulate P in the soil, as also pointed out by others (Jeng et al. 2006, Chen et al. 2011). The surplus was lower for MBMm, as this product had a higher N:P ratio. The surplus was also lower in the silt loam, where P uptake in plants was higher. Although P balances are always site-specific, our results indicate that bi-annual application of bone-rich MBM as N fertilizer would lead to considerable P accumulation. Meat-rich MBM would result in lower surpluses. However, as the P_{AL} values were still high in comparison with P_{Olsen} three years after MBMm was supplied, it is reasonable to believe that hydroxyapatite originating from MBM was still present in the soil. In total, P in MBM is best utilized in acidic soils (pH < 6) and when the N:P ratio in the product is high, as it is in meat-dominated MBM.

Although our results suggest that reduced application rates of biosolids and MBM in agriculture should be encouraged with regard to avoiding P accumulation, reducing product loads can be contradictive to what a farmer regard as beneficial for N supply or soil amendment effects (Refsgaard et al. 2004). As long as biosolids and MBM application in agriculture is politically encouraged, it is difficult to enforce strict limitations on permissible P application rates, as this might reduce farmers' interest in using the product. Thus if we want to keep on using biosolids and MBM products in their present form in agricultural soils, we will probably have to accept a certain P accumulation in the soil. As an alternative, we should encourage the development of products designed to be more P efficient.

Conclusions

Biosolids and meat and bone meal should be regarded as slow-release fertilizers contributing P to plants beyond the first season. However, their contributions to P supply were highly influenced by product- and soil properties. Of the five tested products, only 10−20 tons dm ha^{-1} of the limed, digested biosolids could supply ryegrass with similar amount of P as annual NPK fertilization in the third season. For meat and bone meal, long term contributions to plants' P supply was better in soil with pH < 6 than in soil with pH in the near neutral range. All products influenced extractable P in the soil (P_{Olsen} and P_{AL}), but to varying degrees. P_{Olsen} was more suitable as an indicator of plant-available P in the soil than P_{AL}, which had limited relevance for soils fertilized with meat and bone meal. Compared with annual application of mineral P fertilizer, the main problem with meat and bone meal and biosolids appeared to be their limited ability to supply P in early season. Early season P uptake was comparable with that of annual mineral P addition only when the waste-based products elevated extractable P in soils the most. Combination with low annual applications of mineral P fertilizers should be explored. When application rates for biosolids and meat and bone meal are decided on the basis of soil amendment effects or N fertilizer effects, accumulation of P in soil can be very high, especially with digested biosolids and bone-rich meat and bone meal. The highest application rates accumulated more P in the soil, but additional contribution to longer-term P supply to plants was limited in comparison to the lower application rates. With regard to utilization of the P resources in the products, the lower application rates are therefore preferable.

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