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The Potential for Direct Application of Papermill Sludge to Land: A greenhouse study

Norris, M. and Titshall, L.W.*

Soil Science, School of Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville 3209, Pietermaritzburg, South Africa

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ABSTRACT: Papermill sludge (PMS) is the waste product from the paper manufacturing industry and is produced in considerable quantities worldwide. This investigation characterised a PMS from a papermill plant in South Africa and investigated the potential for direct land application of the PMS to soil. In a pot experiment, application of PMS to three contrasting soils at equivalent rates of 0, 10, 20 and 40 Mg/ha resulted in an overall decline in ryegrass yield. Plant germination was reduced at an application rate of 40 Mg/ha, which was attributed to the high EC of the PMS. The nitrogen content of the ryegrass foliage declined with an increase in PMS application rate, this attributed to assimilation of N by organisms in the presence of excess C from the PMS. Other foliage nutrient and metal concentrations were generally either within critical ranges or below detection limits. This was attributed, in part to either low initial concentrations in the soil and PMS, the liming effect of the sludge or, for some nutrients, microbial assimilation processes. An equilibration time period between land application and crop planting is recommended.

Key words: Land application, Pot experiment, Ryegrass, Waste disposal, Soil amendment

INTRODUCTION

The production of pulp for paper manufacture, either from virgin wood or recycled paper, generates large quantities of solid waste (Norrie and Fierro, 1998). These wastes include wood and bark, sludges, ash and recausting material and other miscellaneous residues (Beauchamp *et al.*, 2002). Papermill sludges (PMS) represent the majority of these wastes (87 %) with the production of one tonne dry paper producing about 50 kg dry sludge (Norrie and Fierro, 1998). These sludges are complex mixtures of chemically modified wood fibers, inorganic solids and chemical additives used in the paper manufacturing process (Charest and Beauchamp, 2002; Monte *et al.*, 2008). Papermill sludges, along with other papermill wastes, have been traditionally disposed of through incineration or landfilling (Beauchamp *et al.*, 2002). The rising costs of these disposal techniques combined with increasingly stringent environmental legislation and a rise in production volume has resulted in the investigation of alternative uses for PMS, such as the use as a soil organic amendment or soil conditioner. Current South African waste disposal guidelines encourage waste minimisation, and where unavoidable, beneficial waste reuse (Department of Water Affairs and Forestry, 2005). Thus the agricultural use of PMS would be considered a favourable approach for the disposal of this type of waste. In recent years, research into alternative methods for the disposal of PMS has focussed on agricultural land application (Phillips *et al.*, 1997; Sellers and Cook, 2003; N'Dayegamiye, 2006) and use in surface mine reclamation (Fierro *et al.*, 1999; Green and Renault, 2008). Papermill sludges have also been utilised in a sylvicultural context (Feldkirchner *et al.*, 2003), and as a container culture medium (Norrie and Fierro, 1998; Ou-Yang and Wu, 2002). Papermill sludges have found wide application as soil conditioners. Their greatest use has been in the field of agriculture (Chantigny *et al.*, 2000; O'Brien *et al.*, 2002; Sellers and Cook, 2003; N'Dayegamiye, 2006), perhaps due to the recognition of organic matter as a fundamental component of soil quality and sustainable production.

Direct land application of raw PMS started in the 1950's, where land application was considered a means to facilitate filtration and microbial decomposition of the waste residue (Norrie and Fierro, 1998). The use of PMS to condition or alter a soil's physical properties has received considerable attention (Phillips *et al.*, 1997; Chantigny *et al.*, 2000; Nemati *et al.*, 2000; Sellers and Cook, 2003; N'Dayegamiye, 2006; Nunes *et al.*, 2008; Jemison and Reberg-Horton, 2008).

*Corresponding author E-mail: titshall@ukzn.ac.za

The utilisation of raw PMS as a soil chemical amendment is more complex due to the chemical heterogeneity of PMS, though have been reported to have a positive impact on properties such as cation exchange capacity (Nunes *et al.*, 2008) and heavy metal retention (Battaglia *et al.*, 2003; Battaglia *et al.*, 2007). As a lime amendment, PMS has the potential to increase and buffer soil pH when incorporated at high rates. Primary and deinking PMS often contain marked amounts of $CaCO_3$ (up to 50% on a mass basis) (Reberg-Horton, 2008) and have been utilised extensively as a liming agent in the United Kingdom and northern Europe (Monte *et al.*, 2008). Nunes *et al.* (2008) reports that application of secondary PMS to Mediterranean soils at rates of between 40 and 120 40 Mg/ha had the effect of raising the soil pH by up to two units and resulted in an increase in the concentrations all macronutrients with increases in available phosphorus and inorganic nitrogen.

The successful use of PMS in agriculture must demonstrate, without adverse effects, that crops benefit or soil properties improve from the addition of the sludge (O'Brien *et al.*, 2002). Generally, adverse plant responses have been found after the application of primary and deinking PMS to soil, this attributed to the high C:N ratios of these sludges which cause a decrease in available soil N concentrations during microbial assimilation. For instance, Sellers and Cook (2003) found that the addition of tertiary or deinking PMS to a Gault clay did not improve the nutrient content of the soil. O'Brien *et al.* (2002) attributed the yield decrease of field beans grown in the soil amended with the PMS to the sequestration of N and P for further microbial sludge decomposition. While land-application of these sludges improves many soil physical properties and increases soil organic matter content, supplemental nitrogen is required to avoid yield decreases associated with microbial nitrogen immobilisation (Norrie and Fierro, 1998).

A PMS was supplied by a papermill plant for this investigation. Currently this PMS is disposed of to landfill, incinerated or recycled in to other production processes. As part of an investigation to consider alternative uses and disposal of this PMS it was proposed that the potential for direct land application be investigated. While a number of studies have reported on the effects of direct land application of various PMS's, an understanding of possible effects of land application of this PMS was required. Thus the objectives of this study were to investigate the response of indicator crop grown in different soil types treated with raw PMS (direct land application). Areas of concern are considered and some recommendations for field application are also made.

MATERIALS & METHODS

Papermill sludge, derived from a kraft process, was collected from the papermill plant for use in the pot experiment. The pH and electrical conductivity (EC) of the PMS were measured in saturated paste extracts (Leege and Thompson, 1997). Approximately 500 cm^3 sample was placed in a beaker, saturated with distilled water and allowed to equilibrate for 1.5 hours. pH was measured in the supernatant using a Radiometer PHM210 pH meter with a standard glass electrode. The $EC_{(25\,^{o}C)}$ was measured after the saturated paste was centrifuged at 2500 rpm for 15 minutes, using a Radiometer CDM83 electrical conductivity meter. Biodegradable volatile solids (BVS) was determined by ashing at 500 °C for 10 hours (Leege and Thompson, 1997) and readily oxidizable organic carbon was determined via the Walkley-Black oxidation procedure (Walkley, 1947). Total nitrogen was determined after Kjedahl digest by steam distillation using a Gerhardt Vapodest 1 (Bremmer and Mulvaney, 1982). Total P, S, Ca, Na, Mg, K and Al and trace elements Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn were obtained by inductively coupled plasma emission spectroscopy (ICP-ES; Varion 720-ES) after nitric acid digestion (Slatter, 1998). All analyses were carried out in duplicate and, with the exception of pH, EC and total N, on oven dry samples (dried at 75 °C for 24 hours) (Leege and Thompson, 1997) ground to pass a 2 mm sieve. Moisture content values were determined from the oven-dried samples.

The three soils selected for use in the trial included the A horizons of a Hutton and Shortlands and the sandy E horizon of a Longlands soil form (SCWG , 1994). The Lo soil was sandy and represented an 'unreactive' soil (characterised by a low CEC). The Hu and Sd soils, while similar in chemical composition, were distinguished on the basis of the Hutton being an apedal structure while the Sd was considered strongly structured (SCWG, 1994).

The EC and pH of the soils were measured in distilled water using a Radiometer CDM83 electrical conductivity meter and a Radiometer PHM210 pH meter with a standard glass electrode, respectively. The pH was also measured in 1 M KCl. Extractable base cations (Ca, K, Mg and Na) were determined by saturating with NH_4^+ (1 M ammonium acetate, pH 7) and cation exchange capacity (CEC) by subsequent replacement with K^+ (SCWG, 1994). Calcium, K, Mg and Na concentrations were determined by atomic absorption spectrophotometry (AAS, Varian SpectrAA-200) and NH_4^+ concentrations by steam distillation (Bremmer and Mulvaney, 1982), using a Gerhardt Vapodest 1. Total N was determined by Kjedahl digestion and NH_4^+

by steam distillation (Bremmer and Mulvaney, 1982). Plant available phosphorus was estimated by extracting with AMBIC solution (0.25 M ammonium bicarbonate, pH 8.3) and P was determined colorimetrically (The Non-Affiliated Soil Analysis Work Committee, 1990) on a Varian Cary 1E UV-Visible spectrophotometer (UV-Vis). Exchangeable acidity was measured by extraction with 1M KCl and acidity determined by titration with 0.01M NaOH to a phenolphthalein endpoint (SCWG, 1994). Organic carbon (OC) was determined titrimetrically following potassium dichromate oxidation on < 0.5 mm material (Walkley, 1947).

The effect of the papermill sludge on the growth of perennial ryegrass (*Lolium perenne*) was assessed under glasshouse conditions in a pot experiment. Air-dry papermill sludge (< 4 mm) was applied to each soil at rates equivalent to 10, 20 and 40 Mg/ha (dry mass basis; referred to as M10, M20 and M40, respectively) based on the sludge's initial moisture content, individual soil bulk density and an estimated field incorporation depth of 20 mm. Soil was thoroughly mixed with the required amount of air-dried sludge and transferred into 1.1 L plastic pots and about 10 ryegrass seeds were planted in each pot. Three weeks after germination, the seedlings were thinned to three plants per pot. A basal fertiliser was applied to all treatments after the seeds had germinated to prevent fertiliser burn of the newly germinated seedlings. The nutrient contents of the basal fertilizer varied according to the concentrations of nitrogen, phosphorous and potassium in the respective soils and were based on the fertility analyses and recommendations carried out by the Soil Fertility and Analytical Services Division (KwaZulu-Natal Department of Agriculture, Cedara) for perennial ryegrass establishment in the soils selected for the pot experiment. The pots were placed in a glasshouse and arranged in a randomised complete block design with three replicates. Pots were watered every two to three days with distilled water.

Aboveground foliage was harvested 9 weeks after sowing by cutting the plants 10 mm above the soil surface. The harvested material, which was placed in paper bags, was dried at 65 °C in a forced draft oven. Once dry, plant biomass was determined and the material milled and stored in plastic vials. Analysis of total N was by Kjedahl digest (Bremmer and Mulvaney, 1982) and P, S, Ca, Na, Mg, K, Al, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn determined by ICP (Varian 720-ES) after digestion with nitric acid (Slatter, 1998).

The relationship between ryegrass yield and PMS application rate was determined using the curve fitting function in Genstat 11 (Lawes Agricultural Trust, Rothamsted Experimental Station, 2008). Overall differences between ryegrass yields and foliage nutrient contents were compared by analysis of variance (ANOVA), using the statistical package Genstat 11 . Where overall F-statistics were found to be significant, means were compared by LSD at the 5% level of significance (Genstat 11).

RESULTS & DISCUSSION

The raw papermill sludge is alkaline with higher concentrations of Ca and Na relative to the other base cations (Table 1). The high EC reflects the high concentrations of Ca and Na, also indicating that these salts are present in a soluble form. The amount of ROC (39.3 %) was markedly lower than the amount of BVS, suggesting stable carbon forms in the PMS and possibly other volatile fractions that were liberated during the ashing procedure. The ROC:N and BVS:N ratios were very high, while were similar to that of typical primary sludges (Table 1, Norrie and Fierro, 1998). Macronutrient concentrations (N, P, Ca, Mg, P and S) were also typical of primary sludges, though the Na concentration was markedly higher then reported by Norrie and Fierro (1998) (Table 1).The high Na concentration (and high pH) was attributed to the use of NaOH during the paper manufacturing process. Concentrations of Al, Ba, Cr, Fe, Mn, and Zn are not typically reported for PMS's. However, with the exception of Cr, the values measured here are not likely to be of concern, especially if the PMS is applied to land and the effective concentration of these metals is diluted in the soil. All other metals measured were below instrument detection limits.

The basic physico-chemical properties of the three soils used in the pot experiment are presented in Table 2. The Hu and Sd soils generally had a higher nutrient status, OC content and EC than the Lo soil. The Hu and Sd soils had similar OC and N contents. The Lo soil had the lowest CEC. The Hu soil had the highest clay content while the Lo soil was found to be sandy. There was a highly significant ($P < 0.001$) interaction effect of PMS application rate by soil type on the yield of ryegrass. In the Hu soil, the highest yields were obtained for the M10 and M20 treatments (Fig. 1a), which were significantly ($P < 0.05$) higher than the M0 and M40 treatments in this soil. There was a strong ($R^2 = 0.97$) polynomial growth response, indicating an ideal sludge application rate between 10 and 20 Mg/ha for the Hu soil (Fig. 1a). In the Lo soil, the yields decreased significantly ($P < 0.05$) and linearly ($R^2 = 0.99$) with increasing application rate with the highest yields attained for the M0 treatment (Fig. 1b). In the Sd soil there was also a strong polynomial ($R^2 = 0.98$) yield response to PMS application rate, with an optimal PMS application rate of about 10 Mg/ ha (Fig. 1c). With the exception of the M40 treatment, the yield of ryegrass grown in the Sd soil was higher than in the Lo and Hu soils at all other application rates.

Table 1.Some physical and chemical properties of the papermill sludge (PMS) used in the pot experiment and typical values reported for primary papermill sludges

Parameter	PMS	Typical[a]
Density (g/cm^3)	0.130	-
pH (1:10 paste extract)	9.10	6.4 - 7.6
Electrical conductivity (Ds/m)	2.65	0.19 - 0.7
ROC[b] (g 100/g)	39.26	38-44
BVS[c] (g 100/g)	72.57	-
BVS:N ratio	676	-
ROC:N ratio	367	111-478
N (%)	0.107	0.08-0.4
P (%)	0.278	580-1000
Ca (%)	2.03	2.1-8.1
K (%)	0.060	0.012-0.08
Mg (%)	0.150	0.061-0.032
Na (%)	0.842	0.044
S (mg/kg)	663	1500
Al (mg/kg)	421	-
Fe (mg/kg)	769	-
Mn (mg/kg)	785	-
Zn (mg/kg)	21.2	-
Ba (mg/kg)	106	-
Cr (mg/kg)	61.7	-
Zn (mg/kg)	21.2	-

a Typical values for primary papermill sludges (Norrie and Fierro, 1998).
c: Readily oxidisable carbon (dichromate oxidation)
d: Biodegradable volatile solids (ashing at 500°C for 10 hrs).

Table 2. Basic physical and-chemical properties of the Hutton A (Hu), Longlands E (Lo) and Shortlands A (Sd) soils used in the pot experiment

Parameter		Hu	Lo	Sd
pH	H_2O	5.34	6.05	6.04
	1 M KCl	4.57	4.90	4.94
Electrical conductivity (mS/m)		17.0	4.00	9.00
Organic carbon (g 100/g)		3.44	0.14	3.29
Total N (mg/kg)		2098	533	2063
Extractable P (mg/kg)		10.1	4.05	2.91
Extractable base cations ($cmol_c$/kg)	Ca	6.63	2.06	9.16
	Mg	3.04	0.62	4.88
	K	0.47	0.10	0.37
Cation exchange capacity ($cmol_c$/kg)		12.7	2.54	14.0
Exchangeable acidity ($cmol_c$/kg)		0.21	0.03	0.05
Particle size (%)				
Sand (0.053–2 mm)		11.6	76.6	11.9
Silt (0.002–0.053 mm)		34.4	12.8	45.6
Clay (<0.002 mm)		54.0	10.6	42.5

Poor germination, in particular in the Hu soil, was noted in the M40 treatments, which was attributed to elevated soil EC values (due to PMS addition) and may have also contributed to reduced final yield. It was suspected that in the Hu soil the high clay content may have negatively affected the leaching of PMS added salt to lower portions of the pot, leading to osmotic stress for the newly germinated seedlings. In the sandy Lo and well structured Sd soils the better drainage may have resulted in an increase in salt leaching improving near surface soil conditions for seedling germination. The elevated EC of this PMS could thus potentially limit its rate of application to soils, especially if crops are to grow from seed. It must be noted, however, that pot trials tend to exacerbate potential EC effects as salts are not leached from the pot as would occur under field conditions and, as such, indicates a 'worst case scenario'.

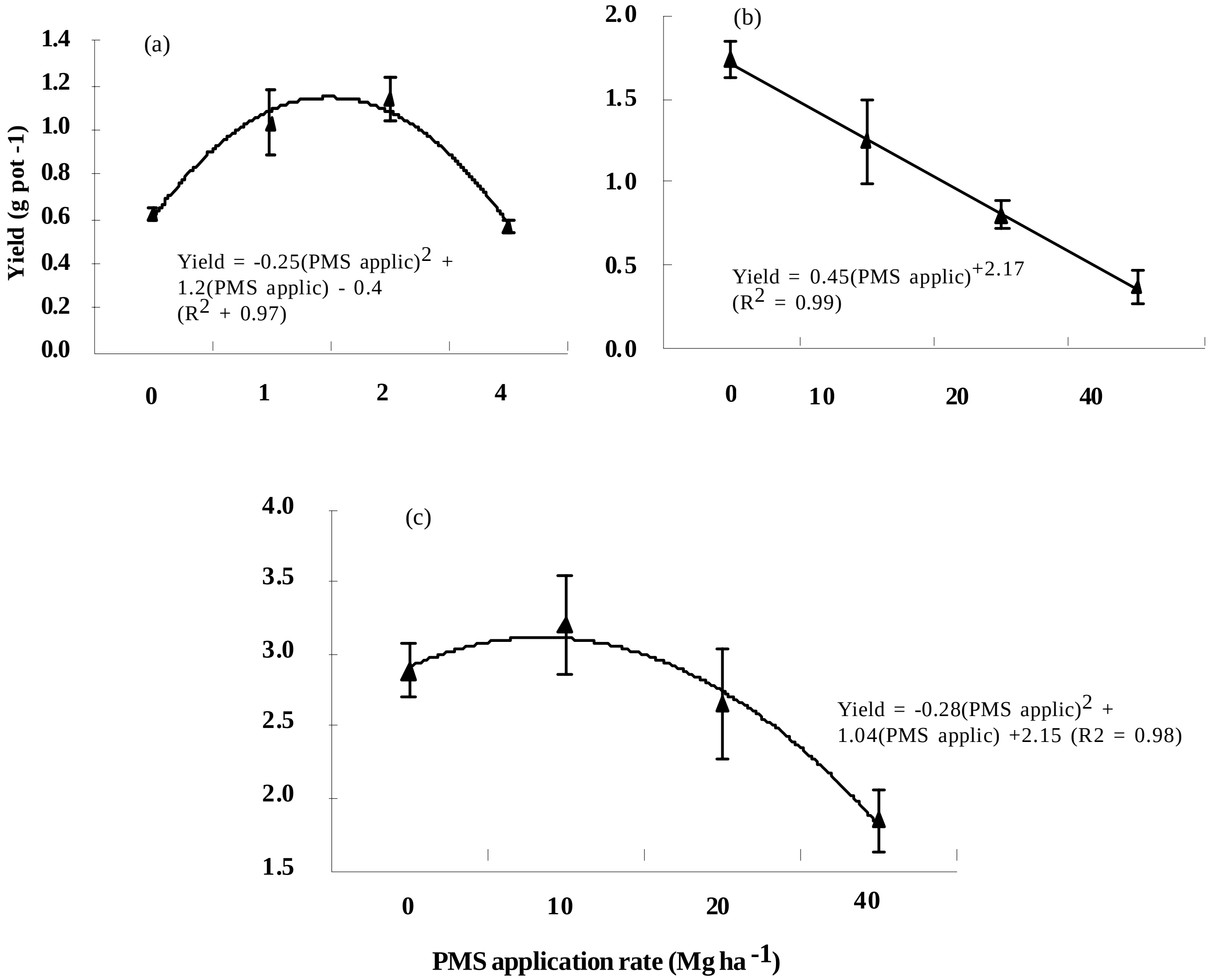

Fig. 1. Mean total yield (± SE, n = 3) for ryegrass grown in (a) a Hutton A, (b) a Longlands E and (c) a Shortlands A treated with papermill sludge (PMS) at rates equivalent to 0, 10, 20 and 40 Mg ha^{-1}. Best fit lines for each soil are presented

Although crop yield response was poor at high application rates (40 Mg/ha) of PMS, the potential long-term benefits should not be overlooked. The land application of PMS has been shown to have a positive impact on a range of soil physico-chemical properties including porosity, bulk density, nutrient and water retention and structural stability (Nemati *et al*., 2000; N'Dayegamiye, 2006).

The overall interactive effect of PMS application rate and soil type on plant total N was significant ($p = 0.014$) and for all soils the N concentrations decreased with an increase in PMS application rate (Table 3). In the Lo soil, plant N concentrations in the M10, M20 and M40 treatments were below the critical values for ryegrass, while in the Hu and Sd soils, plant N contents were only below the critical values for the M40 treatment (Table 3). These data reflect the effect of the addition of a carbon-rich waste to soils, where the availability of nitrogen to the crop is reduced as a consequence of net immobilization processes (Cordovil *et al.*, 2007). The high C:N ratio of the PMS leads to a rapid sequestration of nitrogen by microorganisms. Other studies that have investigated the land application of lignocellulosic materials have reported similar effects (Phillips *et al.*, 1997; Beauchamp *et al.*, 2002; O'Brien *et al.*, 2002). Nitrogen immobilisation was greatest in the sandy Lo soil when PMS was added to the soil. This was attributed to the inherently low N and OC content of this soil (Table 2), which was likely to result in a poor N supplying potential. The low CEC as suggested that any additional NH_4^+ N added (as fertiliser) would not be held by exchange sites thus would be readily available for assimilation as a carbon source (PMS) became available. buffered against Nitrogen losses due to assimilation and sorption processes in the Hu and Sd soils were less marked due to the higher N concentration, OC content and CEC of these two soils (Table 2). However, N immobilistion was still evident in these soils (Table 3). It was also suspected that, in the case of the Hu soil, and to a lesser extent the Lo soil, there was a concentrating effect of N in the ryegrass due to the low yields of these treatments (Table 3).

There were no significant (P > 0.05) differences found between the concentrations of the other nutrients, with the exception of Al, Fe and S (Table 3 and 4) and there were no distinct patterns of uptake by the plants for Ca, Na, P, Al and Fe or Mn (Table 3). The lowest P concentrations were measured in the Hu and Sd soils (Table 2). This was attributed to the higher sorption capacities of these two soils compared to the Lo soil due to higher amounts of Fe and Al oxides in the Hu and Sd soil when compared to the Lo soil. Nonetheless, P concentrations were above the proposed critical value (Table 3), though no clear pattern in the uptake of these was observed. The concentrations of Ca, Mg, K (Table 3) and Fe and Mn (Table 4) in the ryegrass foliage were also all above critical concentration levels and, with the exception of K and Mg of the M40 treatment in the Lo soil, were within the adequate concentration ranges (Table 3). In the case of Al and Fe sample variability was high, which was the likely cause of the significant overall differences that were found (Table 4), though no clear reason for this variability was apparent. The general decline in Mn concentrations with an increase in PMS application rate may be attributed to the liming effect of the PMS (pH 9.10). The bioavailability of these cations is typically reduced when soil pH is raised as variably charged cation exchange sites are deprotonated. Increases in foliage Mn concentrations for the Hu soil M40 treatment may be due to the concentrating effect of low plant biomass (Fig. 1) and increased metal loading at higher application rates.

The foliage S concentrations, for all treatments were, below the critical limit proposed for this nutrient (Table 4), which suggests that the three soils tested were deficient in available S. While the PMS added

contained S, it is suspected, that like N, the addition of a high C source led to rapid assimilation of any available S by microorganisms, resulting in reduced plant uptake. This is supported by the observed decrease in S concentrations of ryegrass as the PMS application rate increased. The Lo soil had the greatest decrease in S concentration as PMS application increased (relative to the PMS treated Hu and Sd soils). This was attributed to the lower anion sorption capacity of this soil (due to lower Fe and clay content as this is a well leached soil), leading to greater mobility of the S for microbial use. The effect on the uptake of S after PMS addition to the Hu and Sd soil was less marked than in the Lo soil.

Concentrations of Cr, Zn and Ba were all below detection in the plant foliage. In the case of this Zn

Table 3. Concentrations of N, P, Ca, Na, Mg and K in foliage of ryegrass grown in a Hutton A, Longlands E or Shortlands A treated with the equivalent 0, 10, 20 and 40 Mg ha^{-1} papermill sludge (n = 3 ± SE). Levels of significance by ANOVA and L.S.D (0.05) are also given for each element. Plant nutrient adequacy ranges and critical nutrient concentrations are also given (Miles, 1994)

Soil	PMS Application Rate (Mg ha^{-1})	N	P	Ca	Na	Mg	K
		%					
Hutton A	0	5.34±0.22a[a]	0.36±0.08	0.78±0.04	0.22±0.06	0.42±0.05	3.96±0.60
	10	5.06±0.21ab	0.31±0.02	0.85±0.11	0.20±0.00	0.39±0.02	3.46±0.11
	20	4.35±0.61be	0.32±0.03	0.62±0.14	0.20±0.03	0.33±0.03	3.20±0.11
	40	3.19±0.81c	0.34±0.02	1.13±0.78	0.27±0.03	0.29±0.04	2.98±0.14
Longlands E	0	4.86±0.50ab	0.78±0.09	0.45±0.09	0.29±0.04	0.31±0.04	3.18±0.13
	10	3.16±0.09c	0.74±0.02	0.46±0.00	0.32±0.07	0.28±0.01	3.12±0.04
	20	2.05±0.04d	0.58±0.22	0.48±0.13	0.23±0.06	0.23±0.06	2.26±0.57
	40	1.86±0.25d	0.88±0.66	0.85±0.74	0.47±0.44	0.14±0.07	2.27±1.20
Shortlands	0	5.04±0.33ab	0.37±0.10	0.49±0.13	0.39±0.20	0.34±0.05	2.35±0.36
	10	4.71±0.41ab	0.51±0.22	0.46±0.11	0.30±0.09	0.34±0.05	2.89±0.71
	20	3.95±0.08ec	0.44±0.01	0.46±0.01	0.39±0.02	0.35±0.01	2.81±0.25
	40	3.40±0.57c	0.48±0.02	0.46±0.02	0.32±0.15	0.32±0.04	2.89±0.17
	P-value	0.014	0.912	0.875	0.694	0.073	0.131
	L.S.D $_{(0.05)}$	0.724	0.387	0.594	0.269	0.039	0.852
Miles (1994)	Adequate	3.6-6.0	0.25-0.36	0.26-1.0	-	0.2-0.5	2.5-6.0
	Critical	3.5	0.24	0.25	-	0.1	2.0-3.0

[a] Letters that are different indicate significant differences between treatment means.

Table 4. Concentrations of S, Al, Fe and Mn in foliage of ryegrass grown in a Hutton A, Longlands E or Shortlands A treated with the equivalent 0, 10, 20 and 40 Mg/ha papermill sludge (n=3±SE). Levels of significance by ANOVA and L.S.D (0.05) are also given for each element. Plant nutrient adequacy ranges and critical nutrient concentrations are also given (Miles, 1994)

Soil	PMS Application Rate (Mg ha^{-1})	S	Al	Fe	Mn
		mg/kg			
Hutton A	0	762±52.9	188±91.5	203±114	115±21.9
	10	812±75.3	169±61.8	179±66.7	96±10.6
	20	818±25.3	213±75.9	173±35.8	82±14.8
	40	789±86.2	449±104	536±28.9	129±105
Longlands E	0	1345±88.8	359±226	397±196	144±1.94
	10	1229±240	122±2.86	159±13.5	131±4.11
	20	714±243	85±46.3	122±36.4	130±48.1
	40	497±253	170±125	162±26.4	88±69.5
Shortlands	0	1180±313	160±142	202±227	89±24.3
	10	1113±111	126±637	170±82.5	88±31.7
	20	1129±235	210±140	102±39.9	81±4.95
	40	1020±109	138±62.6	151±94.5	75±19.1
	P value	0.006	0.011	0.003	0.704
	L.S.D. $_{(0.05)}$	311	176	179	75
Miles (1994)	Adequate	2500-3200	-	50-70	50-300
	Critical	2000	-	-	-

this may lead to deficiencies. The lack of uptake of Cr suggests limited potential for Cr toxicity in the plants, despite the raw PMS containing over 60 mg/kg total Cr. Overall these results are encouraging from a land application perspective where heavy metal toxicity is often the major limitation.

CONCLUSION

The PMS investigated here was a typical product from the paper manufacturing process. Aspects of concern for land application purposes were associated with the unfavourable C:N ratio of the material, high EC (associated with soluble salts) and possibly a Cr toxicity risk. The addition of PMS to these soils resulted in a marked reduction in ryegrass yield at the highest application rate of 40 Mg/ha. This was, in part attributed to the high EC affecting germination and early growth of the seedlings, but also N immobilisation, especially in a nutrient poor, sandy Lo soil. At high application rates this N immobilisation potential, along with the high EC of the PMS, is likely to restrict land disposal of the PMS. In the Hu and Sd soils PMS application rates of between 10 and 20 Mg/ha resulted in the highest yields, suggesting an upper limit for land application. In the Lo soil even the lowest rate of PMS application reduced yield, this attributed directly to nutrient deficiencies induced by microbial processes after PMS addition.

While short-term nutrient effects are, in general, detrimental, the long-term benefits of the mineralisation of organically bound N may be beneficial in that this will moderate N release in the soil. Furthermore, improved soil physical conditions, due to the addition of organic material, should not be disregarded. If physical conditions improved water movement in treated soils, it is possible that any negative impacts associated with the high EC of the PMS may be short-lived due to improved redistribution of these salts in the soil profile.

Pot experiments are useful to indicate likely areas of concern, though in some instances the nature of the pot experiment may exacerbate any observed problems (e.g. high EC). The results from this study suggest that direct land application of the PMS is feasible, though a few considerations need to be taken into account. It is recommended that planting of any crop should not occur with or directly after the application of the PMS to the soil and that an "equilibration" period be allowed. This will reduce the likelihood of N-deficiencies and salt induced problems in the crops. The amount of time for this equilibration will depend on the soil type, temperature, moisture and crop type. Simple tests such as the measurement of soil EC and extractable N may provide suitable indicators to when planting should commence. A further consideration may be the use of additional N (and possibly S) containing fertiliser to reduce the demand on these nutrients in the soil after PMS application.

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