The potential for direct application of papermill sludge to land: a greenhouse study

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Abstract
Primary paper mill sludge (PMS) is a lignocellulosic by-product of the paper manufacturing industry and has traditionally been disposed of too landfill or incinerated. The aims of this study were to investigate the effects of direct land application of PMS on plant growth. In a pot trial, application of PMS to three contrasting soil types at rates of 0, 10, 20 and 40 Mg/ha resulted in an overall decline in ryegrass yield. Poor plant response, which was generally negatively correlated to sludge application rate, was attributed to a high sludge C:N ratio and the resulting microbial sequestration of nitrogen, as well as high electrical conductivity and Na content of the PMS. Concentrations of P, Ca, Mg, Na and K showed variable uptake by the plants with no clear trends evident. While short-term nutrient effects are detrimental, the long-term benefits of improved soil physical conditions and increased soil organic carbon should not be discounted.

Keywords
Land treatment, *lolium perenne*, plant nutrients, nitrogen immobilisation, waste disposal

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 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). In recent years, research to evaluate this disposal alternative has centred primarily on agricultural land application (Phillips *et al.* 1997; Sellers and Cook, 2003; N'Dayegamiye, 2006) and surface mine reclamation (Fierro *et al.* 1999; Green and Renault, 2008). 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). A papermill plant in KwaZulu-Natal, South Africa, produces approximately 10,800 dry t annum^{-1} of primary papermill sludge from its kraft manufacturing process. As an alternative to landfill or incineration, it was proposed that the potential for direct land application of the PMS be investigated. Thus the objective of this study was to investigate the response of indicator crop grown in different soil types treated with raw PMS (direct land application).

Methods and materials

Papermill sludge from a kraft process and three contrasting soils were collected for use in the pot experiment. The soil included the A horizons of a Hutton (Hu, Typic Haplustox) and Shortlands (Sd, Typic Rhodustalf) and the sandy E horizon of a Longlands soil form (Lo; Typic Haplaquept) (Soil Classification Working Group 1994, Soil Survey Staff 2003). Soils were air dried, ground to pass a 2 mm sieve and chemical properties determined following methods of The Non Affiliated Soil Analysis Work Committee (1990). The pH and electrical conductivity (EC) of the PMS were measured in saturated paste extracts (Leege and Thompson 1997). Readily oxidizable carbon (ROC) was determined using the dichromate digestion method of Walkley (1947). Nitrogen was determined by Kjeldahl digestion (Bremmer and Mulvaney, 1982). Total P, S, Ca, Na, Mg, K were obtained by inductively coupled plasma emission spectroscopy (ICPES) after nitric acid digestion (Slatter, 1998).

A pot experiment was used to assess the effect of the papermill sludge on the growth of perennial ryegrass (*Lolium perenne*) under glasshouse conditions. 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). Soil was thoroughly mixed with 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 (based on fertility recommendations for each soil) was applied to all treatments after the seeds had germinated. The pots were placed in a glasshouse and arranged in a randomised complete block design with three replicates. Pots were watered as required with distilled water. Aboveground foliage was harvested 9 weeks after sowing by cutting the plants 10 mm above the soil surface. The harvested material was dried at 65 °C in a forced draft oven and plant biomass determined. The plant material was milled and stored in plastic vials. Analysis of total N was by Kjedahl digest (Bremmer and Mulvaney, 1982) and P, S, Ca, Na, Mg and K determined by ICPES after digestion with nitric acid (Slatter, 1998).

Overall differences between ryegrass yield and foliage nutrient contents were compared by analysis of variance (ANOVA), using the statistical package Genstat 12th edition. Where overall F-statistics were found to be significant, means were compared by LSD at the 5% level of significance.

Results and discussion

Sludge and waste characterisation

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. As expected the ROC:N ratio was high, indicating that additional nitrogen would be necessary to obtain an ideal soil C:N ratio of about 12:1. The ROC:N ratio was similar to that of typical primary sludges (Table 2, Norrie and Fierro, 1998). Macronutrient concentrations (N, P, Ca, Mg, P and S) of the PMS are typical of primary sludges, though the Na concentration was markedly higher then reported by Norrie and Fierro (1998) (Table 2). The high Na concentration (and high pH) was attributed to the use of NaOH during the paper manufacturing process.

Table 1. Some physical and chemical properties of the primary papermill sludge (PMS) utilised for the composting experiment.

Property	PMS	Typical[a]
pH	9.10	6.4 - 7.6
Electrical conductivity (dS/m)	2.65	0.19 - 0.7
ROC[b] (g/100g)	39.3	38-44
ROC:N ratio	367	111-478
N (%)	0.107	0.08-0.4
P (%)	0.278	0.058-1.00
Ca (%)	2.03	2.1-8.1
K (%)	0.060	0.012-0.080
Mg (%)	0.150	0.061-0.032
Na (%)	0.842	0.044

[a] Typical values for primary papermill sludges (Norrie and Fierro, 1998).
[b] Readily oxidisable carbon (dichromate oxidation).

The basic chemical properties of the three soils used in the pot experiment are presented in Table 2.

Table 2. Basic 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 (dS/m)		0.17	0.04	0.09
Organic carbon (g/100g)		3.44	0.14	3.29
Total N (%)		0.210	0.053	0.206
Extractable P (mg/kg)		10.10	4.05	2.91
Extractable base cations‡	Ca	6.63	2.06	9.16
($cmol_c$/kg)	Mg	3.04	0.62	4.88
	K	0.47	0.10	0.37
Cation exchange capacity ($cmol_c$/kg)		12.72	2.54	14.03
Exchangeable acidity ($cmol_c$/kg)		0.21	0.03	0.05

Pot experiment

At the high PMS application rates ryegrass germination was adversely affected. This was attributed to the high EC of the PMS that may have resulted in osmotic imbalance. There was a highly significant ($p < 0.001$) interaction effect of PMS application rate by soil type on the yield of ryegrass. The individual effects of PMS application rate and soil type also had highly significant effects on ryegrass yield. In the Hu soil, the highest yields were obtained for the M10 and M20 treatments (Table 3). This soil had a polynomial growth response (R^2 = 0.97), indicating an ideal sludge application rate between 10 and 20 Mg/ha for the Hu soil (Table 3). In the Lo soil, the yields decreased linearly (R^2 = 0.99) with increasing PMS application rate with the highest yields attained for the M0 treatment (Table 3). In the Sd soil there was a polynomial yield response (R^2 = 0.98) to PMS application rate, with an optimal PMS application rate of about 10 Mg/ha (Table 3). The yield of ryegrass grown in the Sd soil was higher than in the Lo and Hu soils regardless of PMS application rate. In all the soils the yields were lowest at the highest PMS application rate. Other studies involving the land application of lignocellulosic wastes have shown similar results (Phillips *et al.* 1997, Beauchamp *et al.* 2002, O'Brien *et al.* 2002). The decreasing yield at high PMS application rates was attributed to nitrogen immobilization due to the carbon-rich PMS. Nitrogen immobilisation was particularly severe in the sandy Lo soil where an initially low soil nitrogen content exacerbated the deficiency created by microbial N assimilation processes.

Table 3. Mean (n=3) yield and mean concentrations of N, P, Ca, Na, Mg and K in foliage of ryegrass grown in either a Hutton A, Longlands E or Shortlands A treated with the equivalent 0, 10, 20 and 40 Mg/ha papermill sludge (PMS). The adequate and critical concentrations for ryegrass (Miles, 1994) are also given.

Soil	PMS rate (Mg/ha)	Yield (g/pot)[a]	N[a]	P	Ca	Na	Mg	K
			(%)					
Hutton A	0	0.62fg	5.34a	0.36	0.78	0.22	0.42	3.96
	10	1.03de	5.06ab	0.31	0.85	0.20	0.39	3.46
	20	1.14de	4.35be	0.32	0.62	0.20	0.33	3.20
	40	0.56fg	3.19c	0.34	1.13	0.27	0.29	2.98
Longlands E	0	1.73c	4.86ab	0.78	0.45	0.29	0.31	3.18
	10	1.25d	3.16c	0.74	0.46	0.32	0.28	3.12
	20	0.80ef	2.05d	0.58	0.48	0.23	0.23	2.26
	40	0.37g	1.86d	0.88	0.85	0.47	0.14	2.27
Shortlands	0	2.88ab	5.04ab	0.37	0.49	0.39	0.34	2.35
	10	3.20a	4.71ab	0.51	0.46	0.30	0.34	2.89
	20	2.65b	3.95ec	0.44	0.46	0.39	0.35	2.81
	40	1.85c	3.40c	0.48	0.46	0.32	0.32	2.89
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 difference between treatment means (LSD5% = 0.341 and 0.724 for yield and N concentration, respectively).

The overall interactive effect of PMS application rate and soil type on plant total N was significant (p = 0.014) and negative relationship between plant N concentrations and PMS application rate was observed for all soils (Table 3). For the Hu and Sd soils the N concentrations of the ryegrass foliage was below the critical limit suggested by Miles (1994) at the highest application rate of PMS (Table 3). In the Lo soil the N concentrations were below the critical limit for all treatments except the control (Table 3). This supports the argument that at high PMS application rates N is immobilised and plant uptake is decreased.

There were no clear trends found in the uptake of P, Ca, Na, Mg and K by the ryegrass and no overall significant differences were found between treatment means for any of these nutrients. For all treatments the ryegrass foliage concentrations of P, Ca, Na, Mg and K were within the adequate ranges suggested by Miles (1994). Foliage concentrations of Ca, Mg and K were generally higher in the Hu and Sd soils for any given treatment due to the higher base cation content and cation exchange capacities of these soils. Despite the high Na content of the PMS this did not seem to adversely affect Na concentrations in the plant foliage.

Conclusions

Ryegrass growth generally decreased with an increase the application rate of PMS. This was attributed to nitrogen immobilisation, especially in a nutrient poor, sandy soil. The high EC of the PMS also negatively impacted on ryegrass germination at the high application rates. This suggests that land application of PMS may be restricted to lower rates to avoid these problems. However, while short-term nutrient effects may detrimental, the long-term benefits of improved soil physical conditions due to increased soil carbon should not be discounted.

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