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Release of sulphate-sulphur, potassium, calcium and magnesium from spent mushroom compost under field conditions

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Abstract The release of $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} from soil amended with spent mushroom compost (SMC), a byproduct of mushroom production, was measured in leachate from field lysimeters for 30 weeks. Rates of application were 0 and 80 t ha^{-1} moist SMC. The SMC contained 1.7% K, 6.5% Ca, 0.4% Mg and 1.2% S (of which 87% is $\text{SO}_4^{2-}\text{-S}$), and has a C:S ratio of 26. The break-through curves of ion leaching were polymodal indicating the preservation of soil structure in the lysimeters and its influence on leaching. $\text{SO}_4^{2-}\text{-S}$ release from SMC was rapid (first-order exponential) and was very similar to the release from a laboratory incubation. The release of K^+ , Ca^{2+} and Mg^{2+} was described using first/zero-order models which were also used to describe their release in the laboratory. The rate and amount of Ca^{2+} release was similar in the field and laboratory, but the amount of K^+ (and to a lesser extent Mg^{2+}) release was less in the field than in the laboratory. Recoveries of SMC applied nutrients in leachate were 80% of S (263 kg ha^{-1}), 3% of K (14 kg ha^{-1}), 16% of Ca (284 kg ha^{-1}) and 37% of Mg (40 kg ha^{-1}). Little if any S was mineralised. Using SMC could provide plants with S, K, Ca and Mg but there is potential for $\text{SO}_4^{2-}\text{-S}$ losses via leaching.

Key words Spent mushroom compost · Soil · Lysimeter · Nutrient release · Kinetic models

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Introduction

Spent mushroom compost (SMC) or substrate has been reported to be a useful soil amendment for improving soil physical conditions (Wang 1977; Kaddous and Morgans 1986; Stewart et al. 1998d) and chemical conditions providing nutrients for plants (Wang et al. 1984; Stewart et al. 1998a; Maynard 1994). However, few studies have determined the rate or amount of nutrient release from SMC, particularly in field conditions, or for nutrients other than N (Maher 1991; Maynard 1993; Stewart et al. 1998b, c). As the raw materials for producing many inorganic fertilisers are in limited supply, investigating the nutrient supplying potential of byproducts such as SMC is becoming increasingly worthwhile. Maher (1991), using 50:50 mixtures of SMC and peat that were leached every 10 days for 60 days in the laboratory, leached 94% of the K added in SMC. Stewart et al. (1998b) measured the loss of inorganic N from field lysimeters which had received 80 t ha^{-1} of SMC. They recovered in leachate about 5% of the N added in SMC after 30 weeks and attributed the slow rate of N mineralisation to the recalcitrant nature of the organic N in SMC. The rate of field release of mineral N from SMC was slower than measured in a laboratory incubation at 25°C (Stewart et al. 1998b).

Stewart et al. (1998c) measured the release of $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} from SMC amended soil (0–25 cm depth) incubated at 25°C for 16 weeks. They described this release using Eqs. 1 and 2:

$$I_t = M_m(1 - e^{-k_1 t}) \quad (1)$$

$$I_t = M_m(1 - e^{-k_1 t}) + k_0 t \quad (2)$$

where I_t is the amount of cumulative net mineralisation/release over the time period t (weeks), M_m is the maximum amount of mineralisable/releasable nutrient, and k_0 and k_1 are zero and first-order exponential rate parameters respectively. They recorded rapid first-order exponential (Eq. 1) release of $\text{SO}_4^{2-}\text{-S}$ accounting for much of the $\text{SO}_4^{2-}\text{-S}$ applied in the SMC (Table 1)

Table 1 $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} in leachate from soil, and recovered from 80 t ha^{-1} spent mushroom compost (SMC) applications after 30 weeks in the field and 16 weeks at 25 °C in the laboratory

	$\text{SO}_4^{2-}\text{-S}$	K^+	Ca^{2+}	Mg^{2+}
Gross loss from field soil (kg ha^{-1})	21.14	22.23	97.69	13.20
Field recovery of SMC ^a (%)	80.32 ^b	3.24	16.37	36.69
Lab. recovery of SMC ^{a,c} (%)	75.04	44.54	14.12	42.72

^a Above control soil as a proportion of applied

^b Equivalent to 92% of the $\text{SO}_4^{2-}\text{-S}$ applied in SMC

^c Stewart et al. (1998c)

with little if any S mineralisation occurring. The release of K^+ , Ca^{2+} and Mg^{2+} was initially rapid (first order) and then decreased to a constant rate (zero order, Eq. 2, Table 1).

The objectives of this work were to determine the amounts of $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} released from SMC amended soils under New Zealand field conditions and to determine if the models of $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} loss from SMC developed in the laboratory (Stewart et al. 1998c) could accurately describe nutrients released from SMC in the field. The N results from this experiment have been reported by Stewart et al. (1998b) as summarised above.

Materials and methods

Field incubation

The field incubation method using lysimeters has been described (Stewart et al. 1998b). Briefly, undisturbed soil monoliths 176 mm in diameter and 240 mm deep were taken at Lincoln University, Canterbury, New Zealand (latitude 43° 39' south, longitude 172° 27' east). The annular gap between the soil and the casing was filled with liquified petroleum jelly to prevent edge flow during subsequent leaching and the smeared lower surface of the soil monolith was also removed using an acetone/cellulose acetate paste (Cameron et al. 1990). The lysimeters were installed in the field on 23–28 April 1992. The soil was a Templeton fine sandy loam (Udic Ustochrept) with a pH of 5.2 and a 0–240 mm depth bulk density of 1.28 g cm^{-3} (determined by gamma ray attenuation). It contained about 15% clay including illite, hydrous mica, chlorite and vermiculite (Soil Bureau Staff 1968). The soil in the lysimeters was fallow (following cultivation on 22 April 1992 after a sweetcorn crop) and any weeds that grew were removed by hand weeding. Treatments comprised SMC (80 t ha^{-1} moist) and a control, with three replicates of each. The SMC used was mixed with the top 80 mm of soil in the lysimeters on 1 May 1992. The SMC used had a pH of 6.5 and contained 66.7% (w/w) water, 1.8% N (of which 93.5% is organic N), 1.2% S (of which 87% is $\text{SO}_4^{2-}\text{-S}$), 1.6% K, 6.5% Ca and 0.4% Mg on a dry matter basis. This equates to application rates of 328, 440, 1737 and 109 kg ha^{-1} respectively of S, K, Ca and Mg.

The leachate was collected at zero tension beneath each lysimeter in plastic containers that were emptied frequently. The volume of the leachate was recorded, preserved using boric acid, and analysed for $\text{SO}_4^{2-}\text{-S}$ using anion exchange chromatography (with

a conductivity detector), and K^+ , Ca^{2+} and Mg^{2+} using atomic absorption spectrometry. The experiment ran over the winter/spring of 1992, after which time the soil in the lysimeters was subsampled, dried, and sieved (2 mm) prior to analysis. The soil was analysed for total K using a Kjeldahl digestion with salicylic acid followed by atomic absorption spectrometry, organic carbon (C) using a modified Walkley/Black method, and cation exchange capacity (CEC) using a 0.01 M silver thiourea extraction (Blakemore et al. 1987).

Modelling

The net loss of $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} (i.e. loss above that of the control) was modelled. The laboratory-optimised models developed for $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} from the 80 t ha^{-1} SMC treatment of a laboratory incubation experiment (Stewart et al. 1998c) were converted to kg ha^{-1} units. These laboratory-optimised models then provide a tool for comparing loss in the field with that measured in the laboratory incubation. The field-optimised models were developed by fitting the laboratory model to the field data and allowing the laboratory model parameters to change and optimise to this data.

The laboratory-optimised models were also modified to allow for differences in temperature or drainage conditions between the laboratory and the field. The S model was modified to account for temperature differences as described by Stewart et al. (1998b) for N, using the hypothetical relationship between the soil microbial decomposition activity and the soil temperature as used in the CENTURY model (Parton et al. 1987; Metherell et al. 1993). The K^+ and Mg^{2+} laboratory-optimised models were modified to allow for the effect of temperature on desorption from soil, based on the work of Sparks and Jardine (1981), where a decrease in temperature from 25 °C to 3 °C reduced the K^+ desorption rate from soil by a factor of 55–58%. The model parameters were reduced according to this relationship for each leaching interval. The $\text{SO}_4^{2-}\text{-S}$, K^+ , Ca^{2+} and Mg^{2+} laboratory-optimised models were also modified to allow for the lower relative amount of drainage through the lysimeters than through the laboratory incubation tubes, i.e. the parameters for each leaching interval were also expressed on a fractional pore volume basis. The end result was four models for each nutrient, to compare with the measured data (i.e. field-optimised, laboratory-optimised with no modification, temperature-modified laboratory-optimised and drainage-modified laboratory-optimised).

Results

Sulphur

There was a substantial amount of $\text{SO}_4^{2-}\text{-S}$ leached from the SMC; however, it was less than the amount of inorganic S applied in SMC and was very similar to the amount released in the laboratory incubation (Tables 1 and 2, Stewart et al. 1998c). Hence the laboratory-optimised first-order exponential model accurately described the leaching of $\text{SO}_4^{2-}\text{-S}$ in the field (Table 2, Fig. 1). Consequently modifying the laboratory-optimised model to account for the different temperature and drainage conditions in the field underestimated the field $\text{SO}_4^{2-}\text{-S}$ leaching loss (results not presented), as did the century model (Fig. 1). The break-through curves (BTC) of all ions were bimodal with the peak concentrations occurring before one pore volume of drainage had occurred (Fig. 2).

Table 2 Laboratory- and field-optimised parameters (\pm SE), P values from paired t test and r^2 values from first and first/zero-order leaching models describing nutrient release from SMC. *NS*

Optimisation	M_m (kg ha ⁻¹)	k_0 (kg ha ⁻¹ week ⁻¹)	k_1 (week ⁻¹)	P	r^2
SO₄²⁻-S					
Laboratory ^a	253 (4)	–	0.281 (0.023)	NS	0.970
Field	263 (3)	–	0.213 (0.012)	NS	0.976
K⁺					
Laboratory ^a	91 (213)	6.68 (10.27)	0.267 (1.156)	0.000	0.917
Field	7.67 (0.67)	0.202 (0.033)	0.299 (0.052)	NS	0.967
Ca²⁺					
Laboratory ^a	184 (16)	3.87 (0.82)	0.315 (0.058)	NS	0.957
Field	244 (18)	1.20 (0.80)	0.223 (0.026)	NS	0.976
Mg²⁺					
Laboratory ^a	31 (20)	1.07 (0.86)	0.190 (0.178)	0.000	0.865
Field	37 (2)	0.08 (0.11)	0.226 (0.023)	NS	0.978

^aFrom Stewart et al. (1998c)

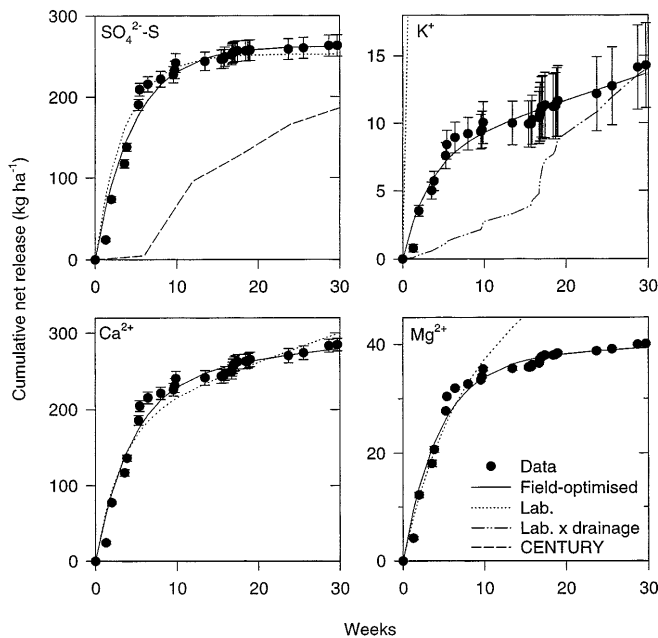


Fig. 1 Field net SO₄²⁻-S, K⁺, Ca²⁺ and Mg²⁺ release from SMC in leachate. Data, and field- and laboratory-optimised model and CENTURY model estimates (*bars* are SEMs)

not significant, i.e. data and modelled curve not statistically different from each other

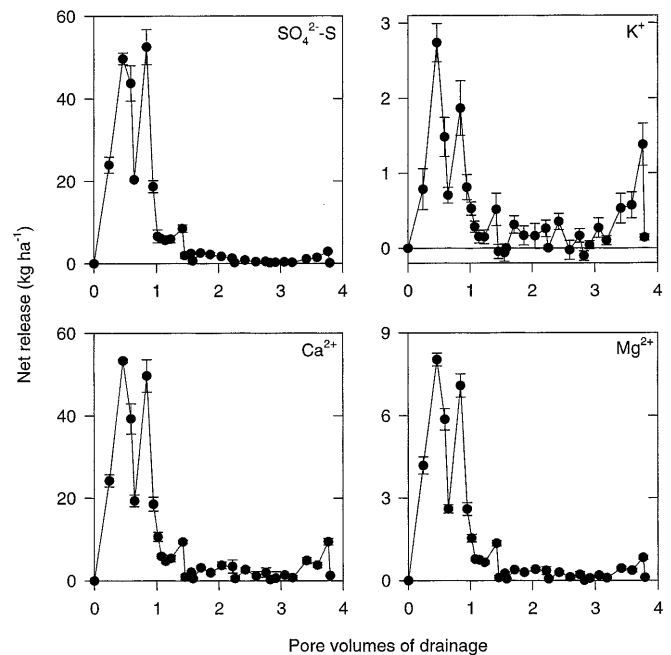


Fig. 2 Break-through curves of the net release of SO₄²⁻-S, K⁺, Ca²⁺ and Mg²⁺ from lysimeters that received 80 t ha⁻¹ SMC (*bars* are SEMs)

Potassium

Only a small proportion of the K in SMC was leached over the 30-week period and this was substantially less than was leached in the laboratory incubation (Table 1, Stewart et al. 1998c). Hence the laboratory-optimised model considerably overestimated the leaching of K in the field whether unmodified or modified to account for field temperatures (i.e. estimated 145 kg ha⁻¹ K loss following temperature modification, Table 2, Fig. 1). The drainage-modified laboratory-optimised model estimated a similar total amount of K loss to that which

was measured; however, the predicted rate of K⁺ leaching was too slow during the first 6 weeks and too rapid at weeks 16–30, in comparison with the measured data (Fig. 1). Allowing for macropore flow in the model could not bring the estimated peak leaching to coincide with the measured data (i.e. it shifted the estimated peak from approximately 17 to 13 weeks, whereas the measured peaks were at 2 and 5 weeks). However, there was a similar relationship between the amount of K⁺ leached and the amount of drainage in the laboratory and the field, although more rapid leaching from macropore flow was apparent initially in the field

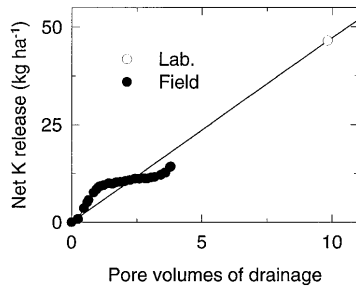


Fig. 3 Comparison of K^+ break-through curves from a laboratory incubation at 25 °C (Stewart et al. 1998c) and from field lysimeters that both received 80 t ha⁻¹ SMC

(Fig. 3). The field-optimised model provided a good fit of the field data (Fig. 1). The BTC of K^+ was similar to the other ions except that it had another peak during the warmer period at the end of the trial (Fig. 2).

Ca and Mg

The proportion of Ca^{2+} leached in the field was similar to the laboratory results whereas a smaller proportion of Mg^{2+} was leached in the field (Table 1, Stewart et al. 1998c). Hence the laboratory-optimised first/zero-order model described the field leaching of Ca^{2+} adequately but it overestimated Mg^{2+} leaching (Table 2, Fig. 1). Allowing for either temperature or drainage differences in the field then underestimated Mg^{2+} loss (i.e. estimated 13 and 3 kg ha⁻¹ Mg loss respectively for temperature and drainage modifications). The pattern of ion leaching was similar in the field to the laboratory as demonstrated by the fit of the field-optimised model (Table 2, Fig. 1).

Effects on soil

By the end of the experiment SMC had increased the soil organic C and total K concentrations at 0–100 mm depth, and the CEC at 0–200 mm depth in comparison with the control treatment (Table 3).

Table 3 Effect of 80 t ha⁻¹ SMC on the soil chemical properties in the lysimeters after 30 weeks

Property	Depth (mm)	Control	SMC	LSD ($P=0.05$)
Organic C (%)	0–100	2.10	2.53	0.20
	100–200	2.18	2.12	
CEC (cmol[+] kg ⁻¹)	0–100	3.37	8.70	1.03
	100–200	3.04	4.48	
Total K (%)	0–100	0.56	0.75	0.14
	100–200	0.71	0.80	

Discussion

The amount of precipitation during the experiment (592 mm) was about 206 mm greater than the long-term mean with much occurring in week 17 (Stewart et al. 1998b). Drainage increased steadily during weeks 0–10 after which it slowed down. There was a lot of drainage during weeks 17–18 but little after that (Stewart et al. 1998b).

The polymodal BTCs that were observed are characteristic of leaching through different regions of soil porosity with little interaction between the regions (McLay et al. 1992). The field soil macro-porosity was preserved in the undisturbed soil monolith lysimeters with the main peaks of leaching occurring before one pore volume of drainage (between 0.4 and 0.9 pore volumes) of the BTC showing that macro-pore flow occurred. Nutrient leaching occurs with less drainage when soil macro-pores are present, compared with repacked soil (McLay et al. 1992).

The large leaching losses of SO_4^{2-} -S that occurred from the SMC were the result of the form and amount of S applied in the SMC (Stewart et al. 1998c). Much of the S in SMC (87%) is present as SO_4^{2-} -S in gypsum ($CaSO_4 \cdot 2H_2O$). The SO_4^{2-} -S was relatively easily released from SMC as it did not need to be mineralised and gypsum is slightly soluble. It was then mainly leached as the soil had a low SO_4^{2-} -S adsorption capacity because it contained little kaolinite, allophane, and iron and aluminium oxides (Soil Bureau Staff 1968). No mineralisation of S may have occurred during this trial which was similar to the results of Stewart et al. (1998c). Dyer and Razvi (1987) also measured large SO_4^{2-} -S leaching losses following compost applications to soil.

The leaching of SO_4^{2-} -S in the field was very similar to that in the laboratory, as indicated by the fit of the laboratory optimised model to the field data (Table 2, Fig. 1). Hence the lower temperature and the smaller amount of drainage in the field in comparison with the laboratory had little influence on the loss of SO_4^{2-} -S from SMC. We would expect the soil temperature to have little influence on the rate of dissolution and movement of the SO_4^{2-} -S added in SMC. Secondly, as SO_4^{2-} -S was leached through soil macro-pores in the field, less drainage was needed to leach most of the SO_4^{2-} -S and the difference in the amount of drainage between the field and the laboratory had little effect (Fig. 2). In contrast, in the laboratory (Stewart et al. 1998c) there were no soil macro-pores but there was excessive drainage (i.e. approximately 80 pore volumes). McLay et al. (1992) also measured considerable macro-pore leaching losses of SO_4^{2-} -S from undisturbed soil monolith lysimeters containing a similar soil to that used in this experiment. The slightly greater amount of S loss in the field compared with the laboratory may be the result of field freezing/thawing and wetting/drying cycles stimulating some S mineralisation (Williams

1967). Surface freezing and thawing was most prevalent between weeks 8 and 15 (Stewart et al. 1998b).

No attempt was made to quantify the effects of differences in the soil structure between the laboratory and the field when nutrient leaching was modelled. Although macro-pores influence the rate of leaching, if there is a large amount of drainage the presence or absence of soil macro-pores may have little influence on the cumulative amount of nutrient leached (Monaghan et al. 1989). This was apparent in this study, as the amount of SO_4^{2-} -S and Ca^{2+} losses were similar in the laboratory and the field irrespective of the soil structural differences between repacked laboratory columns and undisturbed field lysimeters (Table 2, Fig. 1).

Applications of SMC were found to increase the pH and CEC of the soil down to 20 cm depth (Stewart et al. 1998b) which helped to retain K^+ ions against leaching. In the field the SMC was incorporated to 8 cm depth leaving 16 cm of soil below the SMC to adsorb K^+ . In contrast in the laboratory the SMC was mixed throughout the entire soil depth (Stewart et al. 1998c), hence the greater release of K^+ in the laboratory. Wessolek et al. (1983) measured similar amounts of K^+ leaching losses from compost to the field loss in this study. A much smaller proportion of SMC applied K was lost in this work than reported by Maher (1991) (i.e. 3% cf. 94% of applied K). This large difference is a result of the contrasting conditions in the two experiments (e.g. soil cf. peat, field cf. laboratory etc.). The soil used in this field experiment contained clays including illite and hydrous mica capable of fixing K.

The laboratory-optimised model considerably overestimated K^+ loss in the field. However, when the laboratory model was corrected for the lower amount of drainage that occurred in the field, it estimated a similar amount of cumulative release over the duration of the trial to what was measured (i.e. approximately 14 kg ha^{-1}). The more rapid initial leaching in the field than predicted by the laboratory model (Fig. 1) was the result of leaching through soil macro-pores. The laboratory model (Stewart et al. 1998c) was developed using soil that had been sieved and repacked and therefore macro-pore leaching would neither occur nor be predicted.

The relationship between the amount of K^+ leached and the amount of drainage is consistent with the soil chemistry of K. As soil solution K^+ is in equilibrium with exchangeable K, a greater amount of drainage would more frequently and/or more efficiently reduce the concentration of K^+ in the soil solution facilitating K loss from the soil exchange complex. Both Stauffer (1942) and Bertsch and Thomas (1985) reported a similar relationship between the amount of drainage and the amount of K^+ leached from soil.

The release of Ca^{2+} was very similar in the laboratory and the field, whereas less Mg^{2+} was released in the field. This could be related to Mg^{2+} having the highest charge density of the cations measured in this work causing Mg^{2+} to be retained on the soil exchange

complex to a greater extent. Also the differences in wetting and drying cycles and in the depth of incorporation of the SMC between the laboratory and the field could have had an effect.

The similar rates and amounts of SO_4^{2-} -S and Ca^{2+} leached reflected their common origin from the dissolution of gypsum in SMC. The release of SO_4^{2-} -S and Ca^{2+} was surprisingly similar in the laboratory incubation and in field lysimeters given the differences in temperature, drainage, soil structure etc. between them. This shows that laboratory simulations may accurately predict field behaviour. It is apparent from this research that nutrient release from compost is a complex process and many factors interact to influence the rate and amount of this release.

In conclusion the leaching of ions was characterised by polymodal BTC's indicating soil structural effects on leaching processes. Laboratory-optimised models of nutrient loss accurately described field SO_4^{2-} -S and Ca^{2+} leaching, and when modified to account for field soil drainage estimated similar amounts of K^+ loss as was observed in the field. Using SMC could provide plants with large amounts of S and Ca; however SO_4^{2-} -S could potentially be lost by leaching. For this reason SMC should not be applied before periods with excessive drainage on soils with low SO_4^{2-} -S adsorption capacity. The gradual release of K and Mg from SMC is also likely to be useful for plant growth.

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