

Vadose Zone Processes and Chemical Transport

Effects of Spent Mushroom Substrate Weathering on the Chemistry of Underlying Soils

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ABSTRACT

Passive weathering of heaped material in the field is a popular method for treating spent mushroom substrate (SMS) before its reuse. During the weathering process, leachate containing high concentrations of dissolved organic matter and inorganic salts is released into the underlying soils, but effects on soil and ground water quality remain uncertain. We conducted a field study to measure the effects of SMS weathering on chemical and morphological properties of underlying soils. Two SMS piles, 20 m long, 6 m wide, and either 90 or 150 cm high, were placed in a fallow agricultural field dominated by grasses and weathered for 24 mo. Soil samples were taken from each genetic horizon under the SMS piles following their removal and analyzed for pH, total organic carbon (TOC), electrical conductivity (EC), water-soluble organic carbon (WSOC), water-soluble inorganic cations and anions, and exchangeable inorganic cations. Compared with an unaffected control, SMS weathering did not raise soil TOC, but did alter soil pH, and significantly increased EC, WSOC, and water-soluble and exchangeable inorganic ions. At 200 cm below the soil surface, the EC, WSOC, and water-soluble Cl^- , NO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , and K^+ under SMS piles were 4 to 20 times higher than in unaffected soils. Water-soluble NO_3^- was minimal in the surface soil but peaked in the C horizon (120–180 cm) under the 90-cm SMS pile, indicating that these soils may have little capacity for retaining NO_3^- . Concentration profiles of the different solutes reflect their relative mobilities in the soil environment and indicate the potential for effects on subsurface water supplies.

MUSHROOM producers use a specially formulated compost as the substrate for growing the white button mushroom *Agaricus bisporus*. After a few cropping cycles with a given growth medium, mushroom yield diminishes, the compost material is declared “spent” and is replaced with fresh compost. The major components of spent mushroom substrate (SMS) are incompletely composted straw, hay, corncobs, horse manure, poultry manure, gypsum, and some nutrient additives like potash and super phosphate. Spent mushroom substrate represents a valuable, organic-rich resource for agriculture and environmental amelioration (Chong et al., 1991; Wuest and Fahy, 1992; Kuo and Regan, 1993; Levanon and Danai, 1995; Stark and Williams, 1994; Szmids and Chong, 1995). However, high salt content and unstable organic components limit its immediate reuse (Chong and Rinker, 1994; Ciavatta et al., 1993); SMS must be “weathered” on the landscape for 2 yr to facilitate further decomposition of organic matter and the leaching of inorganic solutes (Pennsylvania Department of Environmental Protection, 1997). In the USA,

mushroom production results in the generation of more than 10^6 m³ of SMS annually, with half of the material being generated in Pennsylvania alone.

During the field-weathering process, rainwater passes through SMS piles and leachate is generated. The leachate, which contains high concentrations of dissolved organic matter (DOM) and inorganic salts (Chong and Rinker, 1994; Kaplan et al., 1995; Guo et al., 2001), percolates into the soil and may migrate to ground water. Soil solids have the potential to retain, via adsorption and precipitation reactions, a portion of the leachate solutes, but there are no quantitative data on element concentration depth profiles that result from SMS weathering in the field. Based on volumetric and chemical analyses of SMS and soil leachates, we found that the top 0.9 m of soil may retain from 20 to 89% of the leachate solutes during a typical 2 yr weathering cycle, but the actual flux is highly dependent on solute and SMS pile size (Guo et al., 2001). Wuest et al. (1995) reported that when fresh SMS was applied to a corn field at 0.1 m depth, soil cation exchange capacity (CEC), Mg, K, Ca, and P levels were significantly increased. Kaplan et al. (1995) spread a 46-cm-thick blanket of SMS over a field for 1 yr, and monitored the effect on soil water collected at 1 m depth by vacuum lysimeters and ground water sampled by PVC pipe casing wells. They found that dissolved organic carbon (DOC) in soil water was as high as 880 mg L⁻¹, and concentrations of K^+ , Ca^{2+} , Cl^- , and SO_4^{2-} were more than 1000 mg L⁻¹; DOC, K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} in ground water were raised ca. 5 to 20 times from the background levels.

According to current Pennsylvania Department of Environmental Protection (PADEP) regulations, SMS may be stacked up to a height of 90 cm (3 ft) in fields with a seasonal ground water table ≥ 50 cm below the surface. There is a proposal to increase the allowable height to 150 cm (5 ft). In a companion paper, we reported data pertaining to the solution chemistry of leachate emanating from piles of both heights, including the influence of soil percolation (Guo et al., 2001). However, the extent to which leachate affects the chemistry of underlying soil is not yet known. The objectives of this study were to examine the effect of SMS weathering on soil chemistry and to assess the effect of pile height (90 vs. 150 cm) on resulting solute distributions in the soil profile.

Abbreviations: Control, the control soil profile unaffected by spent mushroom substrate weathering influences; DOC, dissolved organic carbon; DOM, dissolved organic matter; EC, electrical conductivity; Soil 3, the soil profile under the 90-cm spent mushroom substrate pile; Soil 5; the soil profile under the 150-cm spent mushroom substrate pile; SMS, spent mushroom substrate; TOC, total organic carbon; WSOC, water-soluble organic carbon.

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Table 1. Solute release from 2 yr of field weathering of spent mushroom substrate (SMS).[†]

| Component [‡] | 90-cm SMS pile | | 150-cm SMS pile | |
|------------------------|--------------------------------|---|--------------------------------|---|
| | Released from SMS [§] | Volume-weighted mean concentration [¶] | Released from SMS [§] | Volume-weighted mean concentration [¶] |
| Water | 100.7 | – | 80.0 | – |
| DOC | 27.1 | 2691 | 43.4 | 5425 |
| DON | 3.0 | 298 | 4.3 | 538 |
| Cl | 28.3 | 79 | 32.2 | 113 |
| NO ₃ -N | 10.7 | 76 | 2.4 | 21 |
| SO ₄ -S | 22.2 | 69 | 23.9 | 93 |
| PO ₄ -P | 0.36 | 1 | 0.20 | 1 |
| Na | 10.7 | 46 | 9.9 | 54 |
| K | 68.5 | 174 | 63.8 | 204 |
| Ca | 13.1 | 33 | 7.9 | 25 |
| Mg | 6.8 | 28 | 5.4 | 28 |
| NH ₄ -N | 0.77 | 6 | 4.0 | 36 |
| TDN | 14.5 | 1440 | 10.7 | 1338 |

[†] For time series data of leachate chemistry see Guo et al. (2001).

[‡] DOC, dissolved organic carbon; DON, dissolved organic nitrogen; TDN, total dissolved nitrogen.

[§] Units for water are cm. Units for other components are Mg ha⁻¹.

[¶] Units for DOC, DON and TDN are mg L⁻¹. Units for other components are mmol L⁻¹.

MATERIALS AND METHODS

Field Trial

A field experiment was conducted in Chester County, PA. Two SMS piles were deposited in a fallow agricultural field dominated by grasses. The field was used for hay production for more than 10 yr without any SMS application. It has a mean annual precipitation of 1157 mm, a mean annual temperature of 11.9°C (The Pennsylvania State University, 1994), a slope of 5%, and a very deep, well drained, moderately permeable soil formed in residuum weathered from micaceous schist (fine-loamy, mixed, semiactive, mesic Typic Hapludult) (USDA Natural Resources Conservation Service, 1990). The soil type is typical in Chester County, PA where most SMS field weathering is conducted.

The two SMS piles were 20 m long, 6 m wide, and either 90 or 150 cm high (after 30 d of settling). The SMS, which was obtained from Elite Mushroom Co., Avondale, PA, contained 675 g kg⁻¹ of organic matter and 325 g kg⁻¹ of ash (dominantly sulfate salts of Ca and K) on an oven-dry mass basis. The organic matter contained 490 g kg⁻¹ of C and 39 g kg⁻¹ of N. During the SMS weathering experiment from August 1997 to July 1999, a total of 1940 mm of precipitation was received at the experimental site.

The SMS piles were weathered undisturbed for 24 mo and then removed. The total fluxes of water, solutes, and organic matter delivered from the SMS piles to the soil profiles over the 2-yr weathering cycle, as measured by lysimeters under the piles, are given in Table 1 (Guo et al., 2001). On the date of SMS removal, underlying soils were excavated by backhoe, soil profiles were described in the field (Table 2), and multiple soil samples were collected from each genetic horizon and composited. A control profile was excavated, described, and sampled at the same time in an area adjacent to—but unaffected by—the SMS piles. All soil samples were air-dried and passed through a 2-mm sieve prior to analysis.

Analytical Methods

All measurements were made in triplicate. Total organic carbon (TOC) content of soil samples was determined using a TOC-5000A total organic carbon analyzer with an SSM-5000A solid sample module (Shimadzu, Kyoto, Japan). The pH values of soil pastes [soil to solution = 1:1 (w/w), with MilliQ water (Millipore, Bedford, MA) for pH_{H₂O} and 1 M KCl for pH_{KCl}] were measured with a Beckman Φ310 pH meter (Beckman Coulter, Fullerton, CA) and an Orion ROSS 81-

02 combination pH electrode (Thermo Orion, Beverly, MA). Soil water extracts were obtained by shaking soil samples with MilliQ water (1:5 soil to water ratio) for 60 min, centrifuging at 18 500 rpm for 15 min, and passing the supernatant solution through 0.5-μm glass fiber filters (Metrigard; Gelman Sciences, Ann Arbor, MI). Electrical conductivity values (EC) of soil water extracts were measured by an Accumet Model 50 pH/ion/conductivity meter (Fisher Scientific, Pittsburgh, PA) with a YSI 3403 conductance cell (cell constant = 1.0/cm) and an ATC probe to normalize the reading to 25°C. The water-soluble organic carbon (WSOC) content was determined on soil water extracts using a Shimadzu TOC-5000A total organic carbon analyzer with an ASI-5000A auto sampler. Water extracts were also analyzed for inorganic anions Cl⁻, NO₃⁻, SO₄²⁻, and PO₄³⁻ by ion chromatography (Dionex [Sunnyvale, CA] Series 4000I) with an IonPac AS11 (4 × 250 mm) column and cations K⁺, Na⁺, Ca²⁺, and Mg²⁺ by atomic absorption (Video 22 AA/AE spectrophotometer; Instrumentation Laboratory, Lexington, MA). Ammonium acetate (NH₄OAc)-extractable cations were obtained by extracting soils with 1 M NH₄OAc at a 1:10 soil to solution ratio for 5 min under shaking. Exchangeable cations were calculated by the difference between 1 M NH₄OAc-extractable cations and corresponding water-soluble cations.

Data Analysis

Data are presented graphically as the means and 95% confidence intervals of triplicate analytical values, normalized to oven-dry (110°C) soil mass. Soil depth refers to the distance from the ground surface to the middle point of each genetic horizon. For convenience, soil profiles under the 90-cm (3-ft) and 150-cm (5-ft) SMS piles are referred to hereafter as Soil 3 and Soil 5, respectively. The Control profile is that which was sampled in the same field, but was not subjected to the effects of SMS weathering.

RESULTS AND DISCUSSION

Soil Morphology

The SMS weathering affected soil morphology as described in the field (Table 2), including horizonation, texture, color, and structure, especially for the surface soil horizons. For example, the Control soil contains a 13-cm-thick surface horizon that is dark brown in color (7.5YR 3/3), with a strong, granular structure. In con-

Table 2. Description of soil profiles beneath (Soil 3 and 5) and adjacent to (Control) the spent mushroom substrate (SMS) piles.

| Genetic horizons | Depth cm | Texture | Color | Structure | Moist consistence |
|------------------|-------------|-----------------|-----------|------------------|-------------------|
| Control | | | | | |
| Ap1 | 0–13 | silt loam | 7.5YR 3/3 | strong, granular | very firm |
| Ap2 | 13–27 | silt loam | 7.5YR 4/4 | strong, blocky | firm |
| AB | 27–40 | sandy loam | 7.5YR 4/3 | weak, blocky | firm |
| Bt1 | 40–58 | sandy loam | 7.5YR 4/6 | moderate, blocky | firm |
| Bt2 | 58–86 | sandy loam | 7.5YR 5/6 | moderate, blocky | firm |
| Bt3 | 86–112 | sandy loam | 10YR 5/6 | moderate, blocky | firm |
| BC | 112–125 | loam | 10YR 5/8 | weak, blocky | firm |
| C1 | 125–141 | loam | 7.5YR 5/6 | massive | very firm |
| C2 | 141–200+ | loam | 2.5YR 4/6 | massive | very firm |
| Soil 3 | | | | | |
| Ap1 | 0–4 | loam | 7.5YR 3/1 | moderate, platy | firm |
| Ap2 | 4–18 | silt loam | 10YR 4/2 | weak, granular | firm |
| BA | 18–33 | silt loam | 10YR 5/4 | moderate, blocky | firm |
| Bt1 | 33–58 | sandy loam | 10YR 5/6 | moderate, blocky | firm |
| Bt2 | 58–76 | sandy loam | 10YR 5/8 | moderate, blocky | firm |
| CB | 76–93 | sandy loam | 5YR 4/6 | weak, blocky | very firm |
| C1 | 93–120 | loam | 2.5YR 4/6 | massive | firm |
| C2 | 120–180 | loam | 7.5YR 5/8 | massive | firm |
| C3 | 180–200+ | fine sandy loam | 2.5YR 4/4 | massive | very firm |
| Soil 5 | | | | | |
| Ap1 | 0–17 | loam | 10YR 3/1 | moderate, blocky | very firm |
| Ap2 | 17–23 | silt loam | 10YR 4/3 | moderate, blocky | firm |
| BA | 23–35 | silt loam | 2.5Y 4/3 | weak, blocky | firm |
| Bt1 | 35–48 | sandy loam | 10YR 4/4 | weak, blocky | firm |
| Bt2 | 48–60 | sandy loam | 10YR 4/3 | moderate, blocky | firm |
| BC | 60–78 | sandy loam | 10YR 5/6 | moderate, blocky | firm |
| C1 | 78–93 | sandy loam | 7.5YR 5/6 | massive | firm |
| C2 | 93–200+ | fine sandy loam | 5YR 4/6 | massive | firm |

trast, Soil 3 has a surface horizon of 4 cm depth that is very dark gray in color (7.5YR 3/1), with a moderate, platy structure. Soil 5 has a surface horizon of 17 cm depth that is dark in color (10YR 2/1), with a moderate, blocky structure. The thickness and color of the surface soils suggest that Soil 5 retained more leachate organic matter than Soil 3.

Soil pH

Compared with the Control, pH_{H2O} of the surface horizon decreased in Soil 3 by 0.8 units but increased in Soil 5 by 1.4 units (Fig. 1). This difference between the soils is probably a result of the development of surface soil anoxia in Soil 5, whereas oxic conditions prevailed in Soil 3 (Guo et al., 2001). Changes in the subsurface horizons were within 0.4 units (Fig. 1). These modest changes in soil pH are not expected to significantly affect subsequent plant growth.

Changes in pH_{KCl} showed patterns similar to pH_{H2O}, but the pH_{KCl} values are generally lower, reflecting the effect of K⁺ exchangeable acidity. The difference between pH_{KCl} and pH_{H2O} (ΔpH), which is an indirect measure of exchangeable acidity, is higher through much of the soil profile for the Control than for Soil 3 or Soil 5. Evidently, exchangeable acidic cations (H⁺, Fe, and Al) have been replaced by leachate-derived K⁺, Na⁺, Ca²⁺, and Mg²⁺ in soils under the SMS piles.

Electrical Conductivity

Soil EC (Fig. 2) was greatly increased by SMS weathering, especially in the surface horizon, from 0.1 dS m⁻¹

(Control) to 3.43 dS m⁻¹ (Soil 3) and 1.78 dS m⁻¹ (Soil 5). Since these high EC values for the SMS-affected soils were obtained at a soil to water ratio of 1:5, they

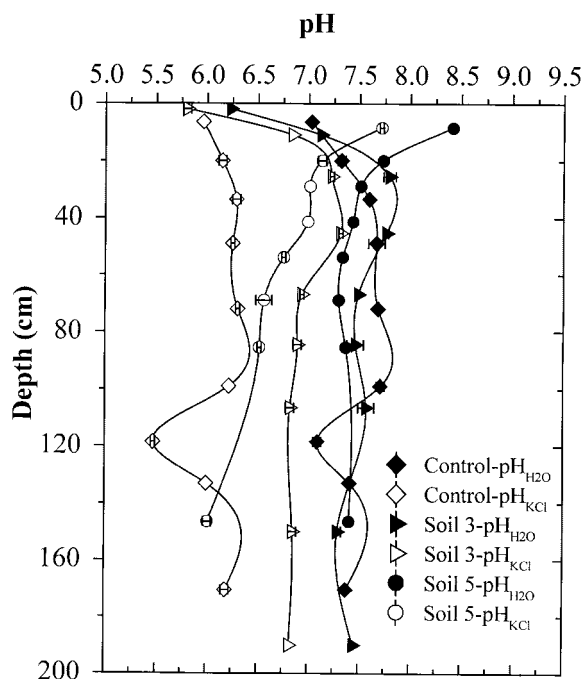


Fig. 1. The pH profiles of soils influenced by spent mushroom substrate weathering (soil to solution = 1:1). Measurements made in 1 M KCl and in deionized water are compared. Depth represents the distance from the surface to the middle point of each genetic horizon. Error bars represent 95% confidence intervals of the triplicate means.

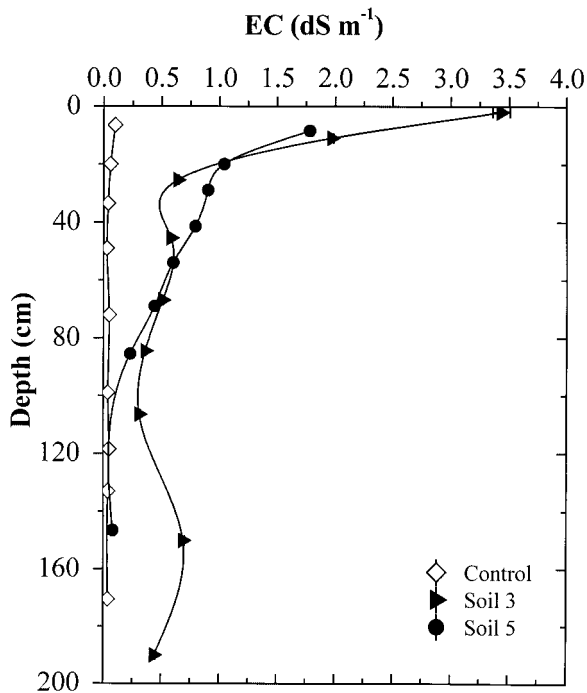


Fig. 2. Electrical conductivity profiles (soil to water = 1:5) of soils as influenced by spent mushroom substrate weathering. Error bars represent 95% confidence intervals of the triplicate means.

probably provide a low-end estimate of the EC values encountered by plant roots. Soil solution EC values in excess of 1 dS m^{-1} are known to induce osmotic stress; plant injury is observed when soil water EC is greater than 4 dS m^{-1} (Plaster, 1992). Although these soils are unsuitable for growing crops right after the SMS removal, continued flushing of salts below the rooting zone should alleviate the problem with time. Deep leaching of salts is evidenced in these soils by the fact that even at 200 cm depth (the deepest sampling point in this study), soil EC was 10 times greater under the 90-cm depth of SMS than the Control (Fig. 2). Depth trends in EC do not indicate deep salt penetration for Soil 5, probably because of diminished water infiltration with the greater SMS depth (Table 1). The Pennsylvania Department of Environmental Protection requirement of a 2-yr "resting" period before the same field is reused for SMS weathering (Pennsylvania Department of Environmental Protection, 1997) seems appropriate to prevent long-term salt accumulation.

Soil 3 had higher EC than Soil 5 at depth (60–200 cm), suggesting more rapid transmission of salts in soil under the shallower pile. In addition, the EC of Soil 3 peaks at the surface and at 150 cm, while that of Soil 5 decreases with soil depth (Fig. 2). This difference probably reflects the greater capacity for storage of precipitation-derived fresh water in the deeper SMS pile. Greater storage capacity was reflected in a 20% reduction in leachate volume (and an equivalent reduction in salt mass) discharged from the 150-cm pile, relative to the 90-cm pile, over the 24-mo period (Table 1; Guo et al., 2001).

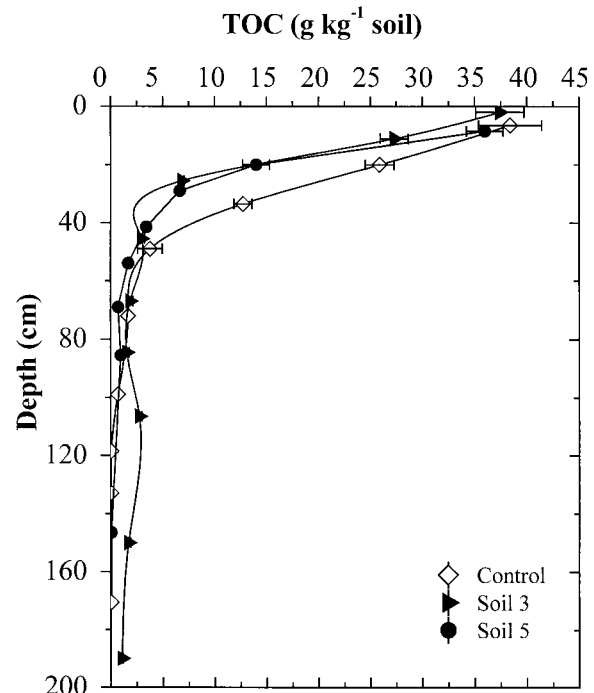


Fig. 3. Total organic carbon profiles of soils influenced by spent mushroom substrate weathering. Error bars represent 95% confidence intervals of the triplicate means.

Total and Water-Soluble Organic Carbon

Spent mushroom substrate weathering did not change significantly the soil TOC content in the surface soils (Fig. 3). Evidently, the darker color observed in surface soils below the 90- and 150-cm SMS piles (Table 2) is due to surficial organic coating of the mineral matrix. As is typical of grassland vegetation, the Control exhibited relatively high TOC. Although the 90- and 150-cm SMS piles released 27 and 43 Mg ha^{-1} of DOC, respectively, during the 2-yr experiment (Guo et al., 2001), the effect of leachate organic matter on soil TOC in the near surface was relatively small.

Conversely, SMS weathering increased WSOC markedly, especially in the upper soil horizons (Fig. 4). For Soil 5, WSOC was highest in the surface horizon and it decreased with soil depth. However, for Soil 3, WSOC increased with depth to a maximum in the 18- to 33-cm horizon and decreased thereafter. Toward the end of the weathering period, DOC concentrations in the 90-cm pile leachate were much lower than at early weathering times (Guo et al., 2001). Evidently, lower DOC solutions flushed previously retained WSOC from the surface horizon and deposited it in the subsoil. In contrast, leachate from the 150-cm SMS pile remained high in DOC until the piles were removed. At depths greater than 90 cm from the surface, Soil 5 and Control WSOC values were similar, while Soil 3 produced significantly higher WSOC throughout the depths studied. These results indicate that leachate organic matter has migrated to a greater depth under the 90-cm pile.

It is noteworthy that the deep migration of DOC in Soil 3 appears to have increased the TOC significantly at depth (see data for 110 to 200 cm in Fig. 3), and only

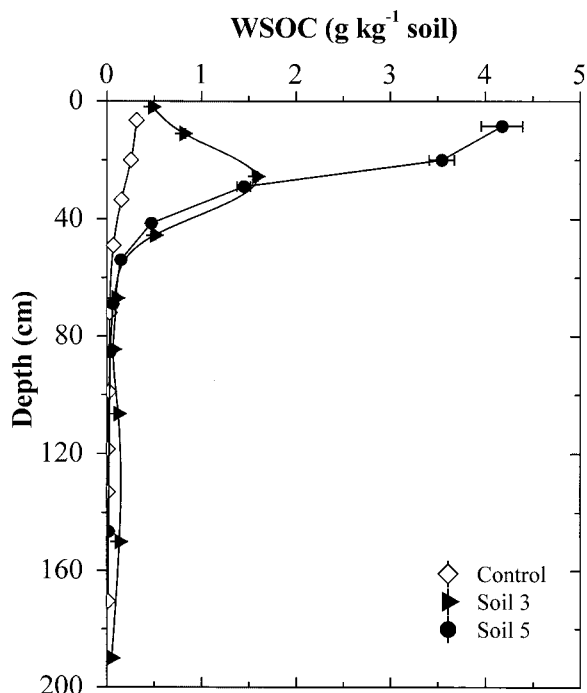


Fig. 4. Water-soluble organic carbon profiles of soils as influenced by spent mushroom substrate weathering. Error bars represent 95% confidence intervals of the triplicate means.

a fraction of this material is soluble in water (Fig. 4). Evidently, some of the introduced organic matter is strongly retained on mineral surfaces in the finely divided matrix of the subsoil.

Water-Soluble Inorganic Salts

Major cations and anions in SMS leachate are K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , and NO_3^- (Guo et al., 2001). Water-soluble concentrations of these inorganic ions were found to increase substantially in soils underneath the SMS piles (Fig. 5). The concentration profiles of the different ions reflect the combined effects of their relative mobilities in the soil and the competitive effects of other ions. In the surface horizon, water-soluble Ca, Mg, and SO_4 concentrations were much higher in Soil 3 than in Soil 5 (Fig. 5). The higher Ca concentration reflects the greater input in SMS leachate from the 90-cm pile (Table 1). However, SO_4 and Mg inputs (Table 1) were either lower in Soil 3 (SO_4) or not significantly different (Mg). Furthermore, DOC inputs (Table 1) and WSOC (Fig. 4) were both higher in the Soil 5 surface horizon. In both cases, SMS leachate introduces high concentrations of K^+ and SO_4^{2-} (Table 1) into soils that contain predominantly exchangeable Ca^{2+} (Fig. 6), which results in the exchange of K^+ for Ca^{2+} on exchange sites. We speculate that under conditions of higher DOC and lower Ca input to Soil 5, much of the Ca^{2+} (both introduced and released by ion exchange) forms complexes with DOM that either flocculate in the near surface or at depth. However, in Soil 3, where DOC is lower and Ca is much higher, a greater proportion of introduced and exchanged Ca^{2+} is retained in the surface horizon because of precipitation of gypsum

($CaSO_4 \cdot 2H_2O$, $K_{SP} = 2.4 \times 10^{-5}$ at $25^\circ C$; Langmuir, 1997), which is dissolved subsequently during water extraction in the lab. Furthermore, formation of sulfate solids may have coprecipitated Mg^{2+} from the leachate. Therefore, water-soluble Ca^{2+} and Mg^{2+} in the surface horizon of Soil 3 were much higher than in Soil 5 (Fig. 5), where higher DOM and lower Ca may have precluded gypsum precipitation. Precipitation of gypsum was indeed observed within 2 wk of sample storage after filtration ($0.5 \mu m$) of leachate collected from below the 90-cm pile. The higher concentrations of water-soluble inorganic ions at depth in Soil 3 compared with Soil 5 indicate that the 90-cm SMS pile was leached faster than the 150-cm pile, an observation that is also consistent with measured EC (Fig. 2), TOC (Fig. 3), and WSOC (Fig. 4) results. The much higher EC of surface soil in Soil 3 is thus attributed to higher water-soluble Ca^{2+} , Mg^{2+} , and SO_4^{2-} (Fig. 5). Concentrations of water-soluble K^+ , Na^+ , NO_3^- , and Cl^- in Soil 3 are similar to or less than those of Soil 5 (Fig. 5).

The concentration profiles for bivalent and monovalent cations are distinctly different (Fig. 5). Soil 3 shows three peaks in the Ca^{2+} and Mg^{2+} concentration profiles (surface, 50 cm, and 150 cm) and two peaks in the K^+ and Na^+ concentration profiles (surface and 150 cm). In Soil 5, results are similar for the top 100 cm, but no subsoil (ca. 150 cm) peak for bivalent or monovalent cations is observed. Although precipitation at the study site was distributed fairly evenly throughout the year, soil profile leaching occurred mainly during January to March, when evapotranspiration was low (Guo et al., 2001). The subsurface peak concentrations of water-soluble inorganic components were a result of first-year solute flushing (Fig. 5). The difference in depth of maximum concentration in Soil 5 versus Soil 3 is due to lower water flux into the former (Table 1). Peaks in Ca^{2+} and Mg^{2+} profiles at 55 cm in Soil 5 and at 150 cm in Soil 3 are attributed to the first-year water flush (Fig. 5). The second-year water flush resulted in Ca^{2+} and Mg^{2+} peaks at 65 cm for Soil 3 and in the near surface for Soil 5 (Fig. 5). The fact that K^+ and Na^+ from SMS leachate displaced native exchangeable Ca^{2+} can be confirmed by the exchangeable ion concentration profiles (Fig. 6). Also, the absence of K^+ and Na^+ peaks at 55 cm in Soil 5 and at 65 cm in Soil 3 reflects the adsorption of these monovalent ions at shallower depths, at the expense of exchangeable Ca^{2+} and Mg^{2+} .

Differences between NO_3^- , Cl^- , and SO_4^{2-} are also apparent in the concentration profiles. Nitrate concentrations decrease with depth near the surface, but a large increase is observed in the subsoil for Soil 3. No such subsurface peak is observed for Soil 5, as is consistent with lower nitrate concentrations and flux from the deeper pile (Table 1). Guo et al. (2001) concluded that the lower leachate NO_3^- concentrations were due to the development of anoxia in the 150-cm pile. The concentration profile for Cl^- is quite similar to those of the bivalent cations in both the 150- and 90-cm piles. Although a small amount of phosphate (HPO_4^{2-}) was introduced into the soils from the two SMS piles (Table 1), no water-soluble phosphate was detected in the soil

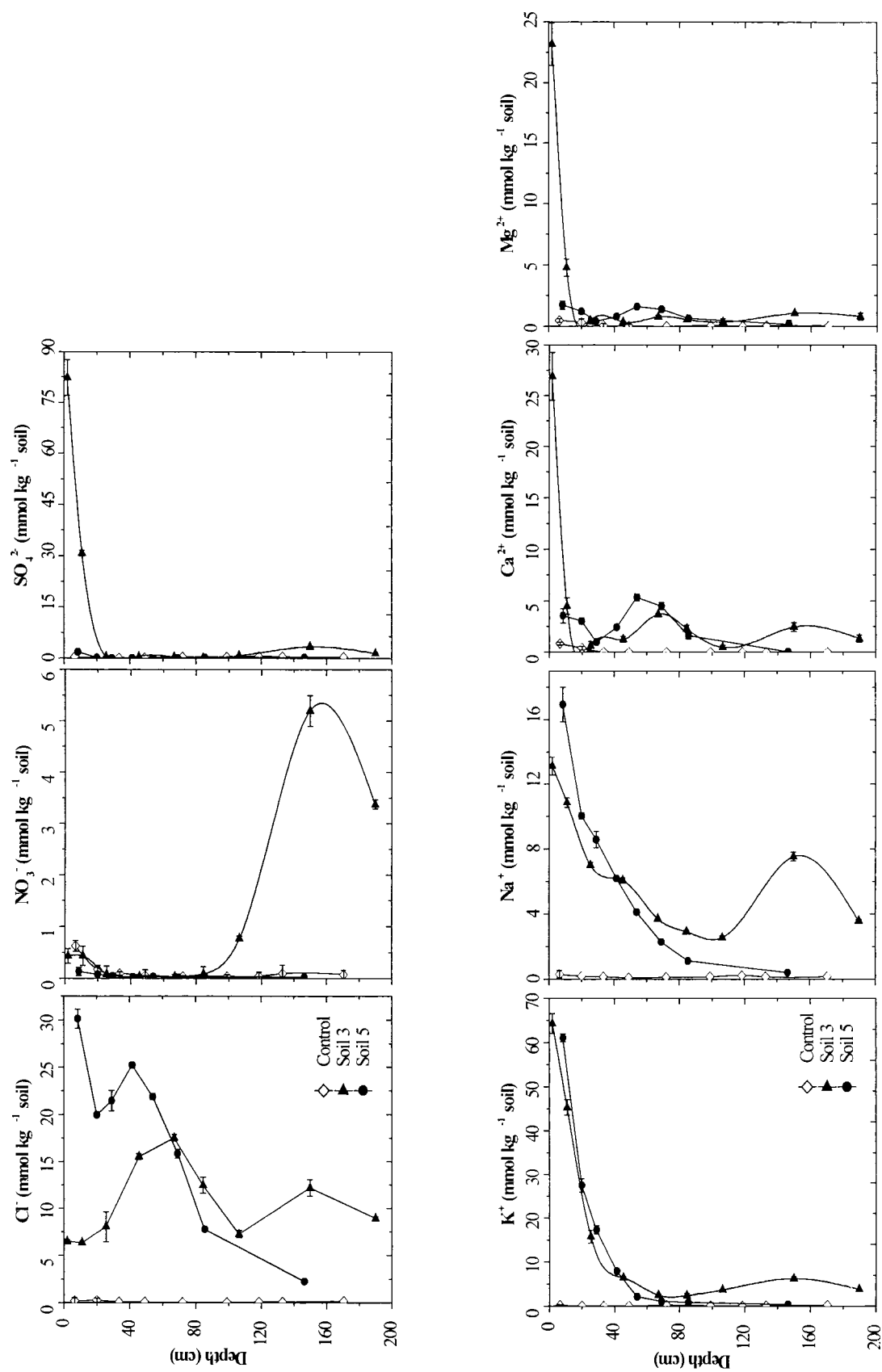


Fig. 5. Water-soluble anion and cation profiles in soils influenced by spent mushroom substrate weathering. Error bars represent 95% confidence intervals of the triplicate means.

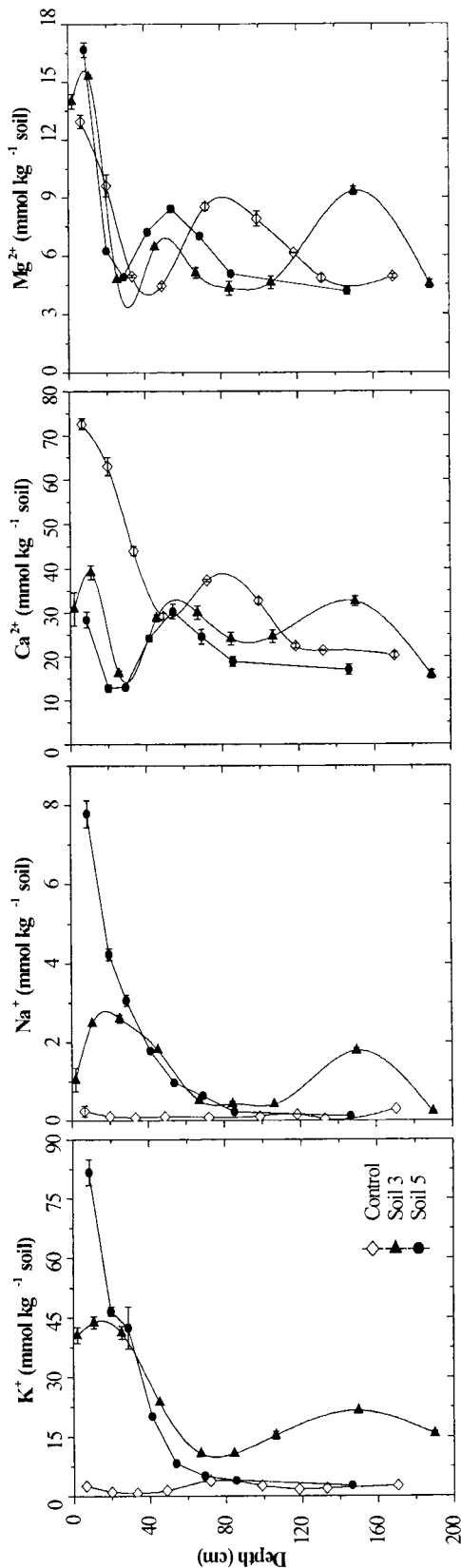


Fig. 6. Exchangeable cation profiles in soils influenced by spent mushroom substrate weathering. Error bars represent 95% confidence intervals of the triplicate means.

water extracts. The field soil contains a high content of iron oxides, and phosphate may form strong complexes with mineral surfaces. The water-soluble cation and anion peaks at 150 cm of Soil 3 (Fig. 5) are consistent with the EC peak at same depth (Fig. 2), and reflect greater leaching from the 90-cm SMS pile.

Exchangeable Cations

Substantive changes in soil exchangeable cations resulted from SMS weathering. In Soil 3 and Soil 5, exchangeable K⁺ and Na⁺ were greatly increased, while exchangeable Ca²⁺ was decreased and exchangeable Mg²⁺ was slightly affected (Fig. 6). This shift in adsorbed ion composition results from the prevalence of K⁺ and Na⁺ in SMS leachate (Guo et al., 2001). Evidently, leachate K⁺ and Na⁺ were adsorbed to the soil and native, exchangeable Ca²⁺ was displaced into the subsoil. Soil 3 showed higher K⁺, Na⁺, and Ca²⁺ than the Control or Soil 5 at 120 to 180 cm depth. The data in Fig. 5 and 6 also indicate a shift from dominantly soluble forms of leachate-derived cations in the near surface to predominantly adsorbed forms at depth. The peak in exchangeable cations at depth in Soil 3 appears correlated with the increase in mineral-sorbed TOC (Fig. 3), which probably elevates the cation exchange capacity above Control levels. The higher exchangeable cation concentrations show the same trend as the soluble levels (Fig. 5), as expected from mass action considerations.

CONCLUSIONS

Field weathering of SMS altered the chemistry of underlying soils. Despite high flux of DOC into the soils, relatively small changes in TOC were observed. However, increases in soil pH, EC, WSOC, and soluble salts were observed. Adsorbed forms of K⁺ and Na⁺ were increased at the expense of native Ca²⁺. Many of these effects extended to 200 cm depth in the soil profile. The data also indicated that the SMS organic and inorganic leachate components were leached faster under the 90-cm pile than the under the 150-cm pile. At about 140 cm depth, Soil 5 had similar levels of water-soluble and exchangeable components as did the Control. But even at depths as great as 200 cm, Soil 3 had 4 to 20 times higher EC, WSOC, and water-soluble Cl⁻, NO₃⁻, Ca²⁺, Mg²⁺, Na⁺, and K⁺ than background values. The differences in solid-phase affinity of the various leachate-derived solutes were also evident. In Soil 3, the nitrate peak eluted through the soil profile most rapidly, emphasizing potential concerns for ground water quality. Leachate solutes have moved at least 200 cm deep in the soil profile during the 2-yr SMS field-weathering process. Field weathering of SMS for 2 yr under the experimental conditions affects ground water with seasonal water tables less than 200 cm and would probably affect ground water at greater depths with time.

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REFERENCES

- Chong, C., R.A. Cline, D.L. Rinker, and O.B. Allen. 1991. Growth and mineral nutrient status of containerized woody species in media amended with spent mushroom compost. *J. Am. Soc. Hortic. Sci.* 116:242–247.
- Chong, C., and D.L. Rinker. 1994. Use of spent mushroom substrate (SMS) for growing containerized woody ornamentals: An overview. *Compost Sci. Util.* 2:45–54.
- Ciavatta, C., M. Govi, and P. Sequi. 1993. Characterization of organic matter in compost produced with municipal solid wastes: An Italian approach. *Compost Sci. Util.* 1:75–81.
- Guo, M., J. Chorover, R. Rosario, and R.H. Fox. 2001. Leachate chemistry of field-weathered spent mushroom substrate. *J. Environ. Qual.* (in press).
- Kaplan, L.A., L.J. Standley, and J.D. Newbold. 1995. Impact on water quality of high and low density applications of spent mushroom substrate to agricultural lands. *Compost Sci. Util.* 3:55–63.
- Kuo, W.S., and R.W. Regan, Sr. 1993. Treatment of carbamate insecticide rinsates using media from the mushroom production industry. p. 663–675. *In* R.F. Wukasz and C.S. Dalton (ed.) *Purdue Industrial Waste Conf. Proc.*, 48th, Purdue Univ., West Lafayette, IN. 10–12 May 1993. Lewis Publ., Chelsea, MI.
- Langmuir, D. 1997. *Aqueous environmental geochemistry*. Prentice Hall, Englewood Cliffs, NJ.
- Levanon, D., and O. Danai. 1995. Chemical, physical, and microbiological considerations in recycling spent mushroom substrate. *Compost Sci. Util.* 3:72–79.
- Pennsylvania Department of Environmental Protection. 1997. Best practices for environmental protection in the mushroom farm community. PADEP 254-5401-001. Bureau of Land Recycling and Waste Management, Harrisburg, PA.
- Plaster, E.J. 1992. *Soil science & management*. 2nd ed. Delmar Publ., New York.
- Stark, L.R., and F.M. Williams. 1994. The roles of spent mushroom substrate for the mitigation of coal mine drainage. *Compost Sci. Util.* 2:84–94.
- Szmidt, R.A.K., and C. Chong. 1995. Uniformity of spent mushroom substrate (SMS) and factors in applying recommendations for use. *Compost Sci. Util.* 3:64–71.
- The Pennsylvania State University. 1994. West Chester local climatological data [Online]. Available at <http://www.ems.psu.edu/PA-Climatologist/westchester/weslcd.html> (verified 24 Apr. 2001). The Pennsylvania State Univ., University Park.
- USDA Natural Resources Conservation Service. 1990. Official soil series descriptions—Chester series [Online]. Available at <http://www.statlab.iastate.edu/soils/osd/dat/C/CHESTER.html> (verified 24 Apr. 2001). USDA-NRCS, Washington, DC.
- Wuest, P.J., and H.K. Fahy. 1992. Spent mushroom compost: Its origin, components and impact on water quality. *Mushroom News* 40:27–33.
- Wuest, P.J., H.K. Fahy, and J. Fahy. 1995. Use of spent mushroom substrate (SMS) for corn production and its effect on surface water quality. *Compost Sci. Util.* 3:46–54.

Waste Management

Viral and Chemical Tracer Movement through Contrasting Soils

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ABSTRACT

Land treatment of animal or human waste can result in chemical and microbial contamination of shallow ground water and/or waterways. We investigated the fate of a host-specific *Salmonella* bacteriophage and a nonreactive chemical (Br^-) tracer when applied to large intact lysimeter soil cores (500 mm diam. by 700 mm high). The soils included a poorly drained Gley Soil and well-drained Pumice, Allophanic, and Recent Soils. A depth of 30 mm of water containing the bacteriophage and Br^- was applied to the soil at a rate of 5 mm h^{-1} followed by up to about 1.8 pore volumes of simulated rainfall. Resulting leachates, collected continuously over at least one pore volume were analyzed for the bacteriophage and bromide (Br^-) tracers. Bromide moved uniformly through the Pumice and Allophanic Soils with peak concentrations at about 1 pore volume, while the bacteriophage was detected only at trace levels or not at all. In contrast, both Br^- and bacteriophage tracers moved rapidly through Gley and Recent Soils, appearing early in the leachate and then tailing off. Such flow patterns in the Gley and Recent Soils are indicative of bypass flow. Coarse soil structure in the Gley Soil, and finger-flow due to water repellency in the sandy Recent Soil are considered responsible for the observed bypass flow in these two soils. Allophanic and Pumice Soils have finer, more porous soil structure leading to a predominance of matrix flow over bypass flow. This study suggests vertical movement of viruses varies significantly with soil type.

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LAND APPLICATION of sewage waste may contaminate receiving ground water by mobilizing entrained viruses through soils with percolating waters (Burge and Enkiri, 1978). Although a number of existing soil-microbial interaction studies have established relationships between soil material and microbial movement, many are limited by the use of repacked soil cores (Isensee and Sadeghi, 1999), soil suspensions (Moore et al., 1981), or topsoil studies only (Gagliardi and Karns, 2000). In such studies, where deeper layers of the soil profile and effect of bypass flow have not been included, movement of applied microbial loads to the soil have not been adequately examined for practical purposes.

Geologically New Zealand is very young and mobile with numerous volcanoes resulting in a diverse landscape with a wide range of contrasting soil types occurring over short distances. There is a paucity of data on the fate of the microbial loads applied to New Zealand soils. Wells (1973) rated the properties of New Zealand soils in relation to effluent disposal and concluded that fine-grained soils from young (2000–7000 yr old) tephra had the ideal combination of soil properties for effluent disposal. However, there were no supporting experimental data. A study of coliforms in leachates from soil cores irrigated with secondary treated municipal effluent by Childs et al. (1977) is difficult to interpret

Abbreviations: PV, pore volume; TSB, Tryptic Soy Broth; PFU, plaque forming units; BTC, breakthrough curve.