SOIL PHYSICAL PROPERTIES AND ORGANIC MATTER FRACTIONS UNDER FORAGES RECEIVING COMPOSTS, MANURE OR FERTILIZER.

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ABSTRACT

A field study was conducted to assess the benefits, with respect to soil physical properties and soil organic matter fractions of utilizing composts from a diversity of sources in perennial forage production. A mixed forage (timothy-red clover (*Trifolium pratense* L.) and monocrop timothy (*Phleum pratense* L.) sward were fertilized annually with ammonium nitrate (AN) at up to 150kg and 300 N ha^{-1} yr^{-1}, respectively, from 1998-2001. Organic amendments, applied at up to 600 kg N ha^{-1} yr^{-1} in the first two years only, included composts derived from crop residue (CSC), dairy manure (DMC) or sewage sludge (SSLC), plus liquid dairy manure (DM), and supplied C to soil at 4.6 and 9.2 (CSC), 10.9 (SSLC), 10.0 (DMC) 2.9 (DM) Mg C ha^{-1}. Soil samples (0-5cm; 5-10cm;10-15cm) were recovered in 2000 and 2001. Improvements in soil physical properties (soil bulk density and water content) were obtained for compost treatments alone. Composts alone influenced soil C:N ratio and substantially increased SOC concentration and mass (+ 5.2 to + 9.7 Mg C ha^{-1}). Gains in soil organic carbon (SOC) with AN of 2.7 Mg C ha^{-1} were detectable by the third crop production year (2001). The lower C inputs, and more labile C, supplied by manure (DM) was reflected in reduced SOC gains (+ 2.5 Mg C ha^{-1}) compared to composts. The distribution of C in densiometric (light fraction, LF; >1.7 g cm^{-3}) and particulate organic matter (POM; litter (>2000µm); coarse-sand (250-2000µm); fine-sand (53-250µm) fractions varied with compost and combining fractionation by size and density improved interpretation of compost dynamics in soil. Combined POM accounted for 82.6% of SOC gains with composts. Estimated compost turnover rates (k) ranged from 0.06 (CSC) to 0.09 yr^{-1} (DMC). Composts alone increased soil microbial biomass carbon (SMB-C) concentration (µg C g^{-1} soil). Soil available C (C_{ext}) decreased significantly as compost maturity increased. For some composts (CSC), timothy yields matched those obtained with AN, and SOC gains were derived from both applied-C and increased crop residue-C returns to soil. A trend towards improved C returns across all treatments was apparent for the mixed crop. Matching composts of varying quality with the appropriate (legume/non-legume) target crop will be critical to promoting soil C gains from compost use.

INTRODUCTION

The return to soil of carbon via application of industrial, municipal, and agricultural organic wastes is one of a suite of restorative practices proposed to redress soil carbon deficits (Lal et al., 1999). While the benefits of manure applications to soil organic C (SOC) have been demonstrated (Gerzabek et al., 1997; Sommerfeldt et al., 1988) only recently have attempts been made to characterize the impact of a broader range of organic amendments on SOC pools (Carter et al., 2004; Chantigny et al, 2000; Paustian et al., 1992). Research is needed to quantify the decomposition rates and effects of composts, sewage sludges (biosolids), and paper and forestry by-products and other diverse organic materials on soil physical properties and SOC under varying climatic conditions (Angers and Carter, 1996).

While opinions differ as to whether composting waste materials prior to application, compared to application of the untreated waste, will promote a net gain in soil C in the long-term (Thomsen and Olesen, 2000; Bernal et al., 1998;), targeting the use of compost to the appropriate crop will be critical to promote soil C gains from compost use (Carter et al., 2004). Lynch et al. (2004) reported that the legume component of a forage legume/grass mixture (~30%) acted as an effective ‘N-buffer’ maintaining forage yield and protein content consistently higher, and within a narrower range, than a grass monocrop, when amended with three different composts. There are relatively few reports on the effect of fertilization on soil organic matter (SOM) when forages are hayed (Franzlubbers et al., 2000; Nyborg et al., 1999), and with some exceptions (Cooper and Warman, 1997), the dynamics of SOM under forages receiving composts remains largely unstudied.

Depending on the frequency of cultivation, nature of tillage and return of amendment C, in short-term rotations SOC gains from the period in forages are often transient in nature and of a highly labile form of organic C (Carter et al., 1994). As intermediate pools of organic matter between fresh crop residues and humified organic matter, densiometric (light fraction (LF)) and size-fractions (particulate organic matter (POM)) of organic matter are considered to be appropriate early indicators of management-induced changes in SOC (Gregorich and Ellert., 1993), and have been widely used to describe the fate of carbon applied in various organic amendments; including straw (Aita et al., 1997) manures (Angers and N'dayegamiye, 1991), paper sludge (Fierro et al., 1999) and composts (Carter et al. 2004). Under perennial crops, or where organic inputs are significant, the nature of, and seasonal variation in these fractions, may play a more significant role in carbon turnover and nutrient cycling than under long-term arable cropping of annual crops (Christensen, 1992).

As the most active fraction of SOM, the soil microbial biomass (SMB) largely controls the accumulation of soil C and N, mineralization of N, P and S and the formation of stable aggregates among other important soil processes. In grassland systems, the annual flux of N (and P) through the SMB can be greater than recovered in the harvested crop (Lovell et al., 1995). Organic amendments often induce rapid and conspicuous changes in the SMB which can be easily measured (Voroney et al., 1993), and these inputs may be expected to alter the structure and function of soil microbial communities. The type, carbon content, and application rate of manures (Rochette and Gregorich, 1998; Paul and Beauchamp, 1996) and composts (Garcia-Lil et al., 2000; Lalande et al. 1998) have been reported to influence the relative response of soil heterotrophic microbes. The impact of composts on microbial biomass and activity has been less intensively assessed under the cool, humid soil conditions of eastern Canada (Carter et al., 2004; ; Lalande et al., 1998; Cooper and Warman, 1997) than in other regions. Soluble organic carbon (C_{ext}) serves as a readily available food source for soil microflora and affects other soil chemical and physical characteristics (Gregorich et al., 1998). Higher levels of C_{ext} can contribute to higher losses of N through denitrification (Tenuta et al., 2000). While the dynamics of C_{ext} as influenced by manure type or ligno-cellulosic organic amendments have been demonstrated (Chantigny et al., 2000; Tenuta et al., 2000), relatively little is known about the concentration and movement of soluble organic carbon in compost amended soils.

In general, the study objectives were to assess the benefits of utilizing composts from a diversity of sources in forage production, with respect to soil physical and biological properties. The specific objectives of the research were to: (i) characterize the short-term changes in soil bulk density and whole soil, size and densiometric fractions of soil organic matter, as affected by forage crop and fertility treatments (composts, manure or fertilizer); (ii) examine the effects of forage crop and fertility treatment on soil microbial biomass and soluble C (iii) characterize the dynamics of compost derived C in soil.

MATERIALS AND METHODS

Field Site Description and Experimental Design

A field experiment was conducted between 1998 and 2001 at Marshwind Farm, Masstown (45°22N 63°23W) near Truro, Nova Scotia on a field site previously maintained continuously in pasture. The soil type is a rapidly drained Hebert gravelly loam (Orthic Humo-Ferric Podzol). The experimental design consisted of a randomized complete block (RCBD) split-plot with four replicates. Main plot units consisted of a 5.5m x 48m strip seeded in spring 1998 to either forage crop; 'Champ' timothy (Phleum pratense L.) alone or a Timothy/'AC Charlie' red clover (Trifolium pratense L.) mixture. Sub-plot units which received fertility treatments were comprised of 4m x 5.5m plots of each crop. Treatments included an unfertilized control, plus the recommended rate (N_{rec}) and a high rate (N_{high}) of mineral fertilizer N for grass (150 kg N and 300 kg N ha^{-1} y^{-1}, respectively) or mixed (legume/grass) forage (40 kg N and 150 kg N ha^{-1} y^{-1}, respectively), applied as ammonium nitrate (NH_4N0_3) (Anonymous, 1991). Organic amendments included treatments of liquid dairy manure (DM), dairy heifer manure compost (DMC), sewage-sludge compost (SSLC) and corn-silage compost (CSC). All organic amendments, except CSC, were applied at up to 300 kg N ha^{-1} y^{-1}. To ensure similar total C inputs from all compost treatments, CSC was applied at 300 kg and 600 kg N ha^{-1} y^{-1} (Table 1). A full description of all treatments, their physical and chemical characteristics, and forage crop response are reported by Lynch et al. (2004). All treatments were surface broadcast and applied as split applications, with 50% of the annual N input rate applied after each of two forage cuts. Mineral fertilizer treatments were applied annually while organic amendments were applied in 1998 and 1999 only.

Soil Sampling and Laboratory Procedures

In October 2000 and 2001, composite (0-15 cm; n=10) soil samples were recovered using a split core sampler (i.d. = 4.8 cm) from fixed locations within each plot. Note: Timothy has a shallow rooting biomass with over 80% of the root biomass in the top 0-15cm of soil (Belanger et al., 1999). The cores were cut into segments and combined to form one composite sample per depth increment (0-5, 5-10, and 10-15 cm). The fresh weight of the composite sample was recorded and moisture content determined from a 20g subsample (105°C; 24h). Samples were passed through a 6 mm sieve to remove gravel, crowns and large roots and visible roots were removed by hand picking. The samples were air dried following three weeks storage at 4°C . Soil bulk density at each depth increment was determined from the sample oven dry weight, inner diameter of core sampler, and sampling depth and corrected for gravel content. Gravel volume averaged 4.97± 2.25% of core volume, assuming gravel density of 2.65 g cm^{-3} (Rowell, 1994). A 50g subsample of air-dried soil was finely ground (<125μm) using a roller-grinder (Smith and Um, 1990). Prior to analyses, inorganic carbon removal was ensured by treating a subsample (approx. 2g) with HCl (1M) for 24h (Midwood and Buotton, 1998). The samples were then washed with deionized water under vacuum filtration, dried at 80°C and reground by mortar and pestle. The C and N content were determined by direct combustion (Dumas method) in the ANCA Preparation Module of a continuous flow isotope ratio mass spectrometer (CF-IRMS) (Europa Tracer/20 Mass Spectrometer, Crewe, UK). Results for bulk soil are presented for 0-5cm depth alone.

In 2000, the light-fraction (LF) organic matter was separated from a 35 g soil subsample by flotation on a 1:2 soil: solution of NaI adjusted to a density of 1.7g cm^{-3} using the method of Gregorich and Ellert (1993). The recovered LF was filtered through a 0.7μm glass fibre filter (Whatman GF/F), washed, dried (48h, 60˚C) and weighed. The entire procedure was repeated to ensure complete removal of any LF entrapped within the heavy fraction pellet. The LF yield from this second separation was typically extremely low. To compare the distribution of soil and amendment C in particulate organic matter (POM) and LF, soil samples (0-5cm depth; timothy plots only) were also separated into four size separates (litter (>2000μm); coarse-sand (250-2000μm); fine-sand (53-250μm); and silt plus clay (<53μm) size) using a modification of the mild mechanical dispersion and wet sieving technique of Aita et al. (1997). All washings along with the silt plus clay (<53μm) suspension were recovered in a 2 l plastic bottle. The slurry was recovered by flocculation with $CaCl_2$ (Gregorich and Ellert, 1993). The particulate fractions were dried at 80°C. The LF and POM fractions were ground to a fine powder (<125μm) in a bead mill (Retsch, Model MM2, Brinkmann Instruments Co., Toronto). Carbonate removal from mineral fractions was ensured as described for bulk soil and the C and N content of a subsample (1mg (LF); 10-20mg (POM, silt plus clay)) determined by ANCA/CF-IRMS. Percent recovery of soil solids following wet sieving was 96.6 (±0.57)% and percent recovery of soil organic carbon was 91.8 (±4.9)%. Aita et al. (1997) and Angers and N'Dayegamiye (1991) found water soluble C comprised 6% to 10% of straw, and manure C, respectively, at application.

The carbon content of soil microbial biomass (SMB) was measured by chloroform fumigation extraction (CFE) using the method of Voroney et al. (1993). Four

25 g subsamples of 6mm sieved field-moist soil were extracted within three weeks of sampling while maintained at 4°C. The filtered (Whatman GF934-AH) extracts (0.5M K_2SO_4) from each pair of control and fumigated subsamples were pooled before analyses. The total C in the fumigated and unfumigated extracts was measured on a Shimadzu TOC Analyzer (Model TOC-5000A, Shimadzu, Kyoto, Japan) with potassium hydrogen phthalate ($C_8H_5O_4K$) as the standard. Microbial biomass C was calculated as the difference in organic C extracted from the fumigated and unfumigated soil samples, divided by a factor of 0.25 to correct for the efficiency of extraction (Kc) of microbial biomass C (Carter et al., 2004). The C extracted by 0.5 M K_2SO_4 (C_{ext}) from the unfumigated soil samples was taken to represent C readily available as a microbial substrate (Chantigny et al., 2000; Tenuta et al., 2000).

STATISTICAL ANALYSES

Statistical analysis of the data was conducted using the General Linear Model of SAS software (SAS Instsitute, Inc., 1999). Where data for both crops is reported the experimental design was a RCBD split-plot with crops as the main block and fertility treatments as sub-plots. Least square means were used to separate significant main and interaction effects, following a protected ($p=0.05$) F-test. Crop x fertility treatment interactions were not significant. Where samples from only one crop were recovered (POM fractions) the data was analyzed as a RCBD.

RESULTS AND DISCUSSION

Soil Physical Properties and Organic Matter Content

Fertility treatments, but not forage crop, affected soil bulk density (Table 2). Among fertility treatments, compost treatments alone reduced soil bulk density (Tables 2 and 3) and increased soil moisture content at sampling ($P<0.01$; data not shown) in both years (2000, 2001). Soil water content increased on a mass basis by compost additions from 2.6% (CSC300) to 6.7% (SSLC300). Carter et al. (2004) attributed the “non-nitrogen” yield benefit of compost applied to potatoes (Solanum tuberosum L.) to a 3.4% by mass increase in soil water holding capacity. Generally, surface soil bulk density decreased with increased soil C concentration, and was lowest for the SSLC300 treatment in both years (Table 2). The benefits of compost use in reducing soil bulk density, and increasing soil moisture retention, were also observed for a variety of composts by Gagnon et al. (1998), and Zebarth et al. (1999).

Forage crop failed to influence bulk soil organic C (g C kg^{-1} soil), C:N ratio, or SOC mass per volume (Mg C ha^{-1}) by the end of the third cropping year (2000) (Table 2). The legume component (~30%) of the binary mixture acted as an effective ‘N-buffer’ maintaining forage yields consistently higher, and within a narrower range, across all fertility treatments (Lynch et al., 2004). As a result, crop C inputs spanned a narrower range of 2.9 (DM300) to 3.5 (CSC600) Mg C ha^{-1} yr^{-1} for the mixed forage crop, compared to 2.2 (control) to 3.6 (N_{high}) Mg C ha^{-1} yr^{-1} for the timothy crop (Table 1). Over the period of the study, however, the additional average C return to soil (~0.33 Mg C ha^{-1}) for the mixed crop was still too small to detect when measured against the relatively large mass of native soil C at planting (14.2 Mg C ha^{-1}; data not shown). Small gains (less than 10%) in bulk SOC can be difficult to detect given the spatial variability of SOC in surface soils, and variability in soil bulk density measurements (Voroney and Angers, 1995). Longer-term (7-10y) studies (Sanchez et al., 2001; 2004), however, support the contention that the 'substrate diversity' provided by combining composts with legumes, may increase the soils capacity to supply N while maintaining soil organic matter levels.

In evaluating the response of SOC to fertility treatments it is important to note that the inorganic fertilizer treatments were applied in all four years of the experiment (1998-2001), while the organic amendments (manure and composts) were applied only during the first two experimental years. N fertilizer at recommended (Nrec) and double the recommended annual rates (Nhigh) failed to produce significant gains in SOC when measured at the end of the third cropping year (2000) (Table 2). By 2001 (Table 3) a significant increase in SOC mass of 2.7 Mg C ha^{-1} was obtained for Nrec, a rate of gain of 0.9 Mg C ha^{-1} y^{-1}. Bruce et al. (1999) suggested rates of accrual of SOC through fertilization of grassland in a "favourable climate" of 0.4 to 0.8 Mg C ha^{-1} y^{-1}. The liquid dairy manure (DM300) produced small gains in both SOC concentration and mass (2.45 Mg C ha^{-1}) in 2000, derived from both improved timothy crop residue returns (Table 1), and C contained in the manure (Table 2). Although applied at a high rate for liquid manure, minimal total C was supplied by this manure treatment (2.9 Mg C ha^{-1}) as compared to the compost treatments (4.6 to 10.9 Mg C ha^{-1}) when applied at equal N application rates (Table 1). As the use of bedding decreases, manures contribute much less to soil C in most farming systems than is commonly perceived (Beauchamp and Voroney, 1994). At a soil quality benchmark site in Nova Scotia, Webb et al. (2000) found manure and crop residue inputs were insufficient to stabilize soil organic matter levels in a corn-forage (alfalfa-timothy) rotation and recorded an 8% reduction, over five years, in topsoil (0-15cm) organic C and N levels (g kg^{-1}).

All compost treatments contributed to substantial increases in soil C concentration and mass per volume one and two years after the last application (1999) (Tables 2 and 3). Composts increased SOC content from 29.3 g kg^{-1} soil for the unfertilized control to a range of 41.5 g kg^{-1} soil (CSC300) to 53.2 g kg^{-1} soil (SSLC300) in 2000 (Table 2). Cooper and Warman (1997) found after three years of application of composted or fresh chicken manure and fertilizer at equivalent N rates to a hay crop, only the composted manure increased soil organic C concentration (14.6 to 15.7 g kg^{-1} compared to 13.9 g kg^{-1} for the control). The gains in SOC of up to 9.7 Mg C ha^{-1} for all compost treatments were achieved at application rates of less than 13 Mg DM ha^{-1} y^{-1} (Table 1). By comparison, Rochette and Gregorich (1998) reported a gain of SOC of 3.4 to 5.3 Mg ha^{-1} on a Humic Gleysol following application of a stockpiled, highly straw-bedded dairy cattle manure, applied for three years at much greater annual rates of 100 Mg ha^{-1} (wet weight) (approx 50 Mg DM ha^{-1}). The total C returned to soil is not a consistently good predictor of SOC accumulation (Sanchez et al., 2004), and changes in SOC produced are often better described by the lignin:N content of crop residues and organic amendments (Paustian et al., 1992; Melilo et al., 1989). For example, while the order of gains in SOC with compost treatments in 2000 was DMC300>CSC600> SSLC300, by 2001, the order of SOC gains was CSC600>DMC300>SSLC300 (+9.0, + 7.6 and + 7.0 Mg C ha^{-1}, respectively) (Table 3). Higher levels of humic compounds and stable forms of C are characteristics of composts of increasing maturity (Inbar et al., 1990). In addition, microbial products produced during composting, may be even more recalcitrant to degradation than lignin (Voroney et al., 1989). Over the period October 2000 to October 2001 SOC levels for treatment CSC600 changed only slightly (3.3%) (25.1 to 24.3 Mg C ha^{-1}; Tables 2 and 3) suggesting this compost was decomposing very slowly in soil (k *~0.05* y^{-1}). In contrast, for the composts of higher C:N (DMC and SSLC), the mass of SOC in the surface soil decreased 11.1% (25.6 to 22.8 Mg C ha^{-1}) and 7.2% (24.0 to 22.2 Mg C ha^{-1}) respectively, over the same period. These carbon balance estimates of CSC turnover were supported by stable isotope techniques (data not shown) which indicated that CSC compost appeared to be mineralizing slowly (k=0.06 yr^{-1}) with 89% of applied compost-C retained in surface soil (0-5cm) two years after last application. Using SOC data from a long term study (37y), Gerzabek et al. (1997) calculated mean decomposition rates of 0.10 y^{-1} for a well decomposed manure compared to 0.048 y^{-1} for applied peat.

The C:N ratio of the coarsely sieved bulk soil (Tables 2 and 3) was consistently increased by DMC and SSLC and the dairy manure from an average for both years of 11.2 for the control soil to 11.5 (DM300), 12.9 (DMC300) and 14.0 (SSLC300). In contrast, when applied at similar total C input rates CSC significantly reduced the soil C:N ratio to 10.2.

Light Fraction and Particulate Organic Matter

Unlike some manures, composts are unlikely to produce improvements in water-stable aggregation (Watts et al., 2001) and fractionation of the whole soil into primary organomineral complexes (clay-, silt-, and sand-sized organic matter) may effectively describe the dynamics of these materials in soil. In contrast to the finer soil fractions (clay- and silt-sized), the quality and degradability of organic matter within the LF and POM fractions, will directly reflect the quality of the incoming plant residues and organic amendments (Gregorich and Ellert., 1993). The fraction of SOC as LF-C decreased with depth (Table 4), and differences between crop and fertility treatments with respect to LF mass, quality (C:N) and fraction of SOC were apparent for the surface depth alone. LF-C as a fraction of SOC was greater (20.2%) for the grass crop than the mixed crop (18.8%). Because of the lower bulk density associated with the timothy crop, however, these differences were not reflected in mass of LF-C per hectare.

Both the LF and the combined POM (>53μm) as a fraction of SOC in the surface soil (0-5cm) increased with C inputs. For all treatments, however, POM comprised a larger fraction of SOC than that obtained by densiometric fractionation at 1.7 g cm^{-3}. For the unfertilized control, POM comprised 38.8% of SOC compared to 8.7% of SOC as LF (Table 4 and 5). Gregorich et al. (1995) similarly recovered approximately threefold more C as POM (>53 μm) than as LF (1.7 g cm^{-3}) from a maize cropped soil. Carter et al. (1994) found macroorganic C (>53μm) comprised 40% of SOC four years after the establishment of temperate forage grasses in Atlantic Canada. Averaged across all treatments total POM (>53 μm) accounted for 82.6% of the difference between fertility treatments and the control in SOC mass (Mg C ha^{-1}).

Inorganic fertilizer treatments (N_{rec}, N_{high}) failed to significantly increase the amount (Mg ha^{-1}) and fraction of SOC comprised of LF or POM or quality (C:N) of these fractions (Tables 4 and 5). The exception was a small shift in the proportion and quality of the coarse sand-sized (>250µm) POM (Table 5). Dairy manure (DM300) significantly increased SOC as LF-C (13.6% vs 8.3% control); the C:N of LF (23.0 vs 21.2 control) and litter fraction (33.1 vs 26.9 control); and the mass of LF (2.41 Mg C ha^{-1} vs 1.26 control) and POM (>250 µm) per hectare. Compost treatments increased LF-C from 4.1 Mg C ha^{-1} (CSC300) and 8.8 Mg C ha^{-1} (DMC300) compared to 1.3 Mg C ha^{-1} (control) and LF-C as a proportion of SOC from 8.3% (control) to 34.1% (DMC300) of SOC (Table 4). Total POM increased with compost treatments up to 66.6% of SOC (SSLC300) compared to 38.8% for the control (Table 5). Compost treatments produced significant increases in the amount of POM (Mg POM-C ha^{-1}) in all size fractions. For some treatments the LF was as effective as POM in characterizing gains in SOC. For DMC300 gains in LF C (+ 7.5 Mg C ha^{-1}) and POM C (+ 8.1 Mg C ha^{-1}), represented 83.2 to 89.3%, respectively, of the gains in SOC. In contrast, a significant portion of SSLC appears to have been recovered in a coarse (>53 µm) but relative dense (>1.7 g cm^{-3}) fraction, as the gain in LF-C (6.1 Mg C ha^{-1}) for SSLC was relatively low compared to wet sieving (10.6 Mg C ha^{-1}). These results are attributable to differences in the nature of these inputs at application. The SSLC contained a higher ash content at application. Given the diversity of organic amendments a range of liquid densities are undoubtedly required for LF separation. In addition, for some organic amendments the movement of C and N through LF and size fractions with decomposition may not necessarily coincide. Fierro et al. (1999) chose LF at 1.8 g cm^{-3} and wet sieving at >53 µm to track the dynamics of a de-inking paper sludge (DPS) in a minesoil and found the material progressively became denser (increasingly recovered in the HF) but remained relatively coarse during decomposition, which was attributed to mineral coatings present on sludge fibers. We chose to separate LF at 1.7g cm^{-3} as the relatively large volume of LF of native organic matter at these sites (up to 20% of SOC) and by these amendment treatments (up to 34% of SOC), would, with higher density liquids, make avoiding contamination of the LF with mineral and organo-mineral material difficult. Combining fractionation by size and density improves interpretation of the dynamics of organic amendments in soil.

The litter fraction (>2000 µm) has traditionally been removed by sieving prior to analysis of soil samples. This fraction often comprises a very small fraction of the total soil mass and total SOC (less than 4% of SOC for control, fertilizer and liquid manure treated soils in the present study, Table 5) and residues of relatively high decomposability typically reside only briefly (<1y) in this fraction (Aita et al., 1997). For some compost treatments, however, even 1-2 years after application, this fraction represented as much as 14% of SOC, and differed from the control by up to 3.0 Mg C ha^{-1}. As it accounted for as much as 41% of the gains in SOC for some treatments, it may be generalized that coarsely sieving the soil, and quantifying the litter fraction, is critical to characterizing the dynamics of composts in soil. Whitney and Zabowski (2004) found excluding the >2mm fraction from 17 varied soils underestimated soil total N by up to 37%.

For the control, inorganic N fertilizer and manure treatments, the C:N of LF (19.4 to 23.0) fell within the range (13 to 36) typically reported for agricultural soils (Janzen et al., 1992). The C:N of POM decreased with fraction size as shown elsewhere (Christensen, 1992) while the C:N of the LF for the unfertilized control was intermediate to that of the two coarsest POM fractions (250-2000µm and >2000 µm)(Tables 4 and 5).

The fine POM (53-250μm) tends to consist of material of lower C:N and in a more advanced state of microbial processing than the LF (Gregorich et al., 1996). The gains in SOM with manure were found largely in the LF and consisted of material of a wider C:N ratio than the LF of the background soil. Large shifts in the quality of LF and specific POM fractions were evident with some compost treatments. The C:N of both the LF (24.6) and all POM fractions (12.8 to 32.0) was significantly wider for SSLC300 than for the unfertilized control (21.2 LF; 12.2 to 26.9 POM), while the DMC300 compost failed to shift the C:N of these fractions. In contrast, the C:N of the LF and all POM fractions was consistently and substantially reduced by CSC treatments (Tables 4 and 5). In grassland soils, and where organic amendments are an important component of the production system, the quality of, and seasonal variation in, POM and LF fractions will play a more important role in C turnover and these fractions may comprise a much larger pool of mineralizable N than under long term arable soils (Christensen, 1992). The present study, suggests some composts (and legumes), can produce a marked shift in the quality of, and potential for N mineralization from, LF and POM fractions. For example, with an average C:N of 10.7, the POM of the CSC600 treatment represented 52.8% of SOC and 1240 kg N ha^{-1}. Assuming an average mineralization rate of 5%, this fraction would contribute up to 62 kg ha^{-1} of plant available N per year.

Soil Microbial Biomass and Available Carbon in Soil

Available C (C_{ext}) concentration ranged from 56.3 μg C g^{-1} soil (control) to 83.2 μg C g^{-1} soil (SSLC300) in the surface soil when measured in Oct. 2000, and was more variable than at the lower soil depth where it ranged from 54.2 μg C g^{-1} soil (control) to 66.5 μg C g^{-1} soil (SSLC300) (Table 6). The concentrations of C_{ext} were significantly greater than the control for the SSLC300 (at both depths) and DMC300 treatments (0-5cm depth). The K_2SO_4-extractable C (C_{ext}) of 48-80 μg C g^{-1} soil measured across both depths sampled is within the typical range of 25 to 100 μg C_{ext} -C g^{-1} soil for soils in Eastern Canada amended with up to 20 Mg C ha^{-1} as organic amendments, including manure or de-inking paper sludge (Chantigny et al., 2000; Tenuta et al., 2000; Gregorich et al., 1998). The higher concentrations of C_{ext} for DMC300 and SSLC300, when measured more than one year after the last application, is consistent with the sustained release of available C from partially degraded organic amendments. Greater (2.6 - 6.7% by mass) soil water contents than the control were found for all compost treatments, and when combined with high levels of available C, can contribute to higher losses of N through denitrification (Tenuta et al., 2000). Tenuta et al. (2000) considered the ability of a solid beef manure to maintain C_{ext} at over 100 μg C_{ext} -C g^{-1} soil over six months (and substantially higher denitrification rates) to be due to the ongoing decomposition of straw. Among compost treatments, C_{ext} decreased as the C:N of the applied compost decreased. The CSC compost, even when applied at comparable total C input rates as DMC300 and SSLC300 , did not differ from the control with respect to C_{ext} concentration (μg C g^{-1} soil). Correspondingly, the percentage of SOC as C_{ext} was highest for the control, Nrec and Nhigh, and lowest for CSC300 and CSC600 (Table 6). This result suggests that C from more mature composts is solubilized much more slowly in soil than that from partially composted materials and solid manures. Soluble C has been shown to decrease with time during composting of a wide range of feedstocks (Wu and Ma, 2002).

Microbial biomass C (SMB-C) per unit soil weight (μg C g^{-1} soil) or as a fraction of SOC was substantially greater in the surface depth for all treatments (Table 6) and differences between treatments were significant only for the surface soil. Much greater SMBC content was obtained for the grass forage (1741.8 μg C g^{-1} soil) compared to the legume/grass forage (1169.3 μg C g^{-1}) although the high variability of values meant treatment differences were not detectable. Drury et al. (1991) found reed canarygrass produced greater microbial biomass C, but not N, than alfalfa. These SMB-C levels obtained are in keeping with the range of 1,000 to 2,000 μg SMBC g^{-1} soil found by Lovell et al. (1995) for a pasture soil under contrasting management regimes.

The highest SMB-C concentration or mass per hectare was obtained for DMC300 (2125.0 μg C g^{-1} soil;1.02 Mg SMB-C ha^{-1}) followed by CSC600 (1868.4 μg C g^{-1} soil; 0.94 Mg SMB-C ha^{-1}) compared to the unfertilized control (1255.8 μg C g^{-1} soil; 0.66 Mg SMB-C ha^{-1}) (Table 6). Lalande et al. (1998) found dairy manure composts increased SMB-C more than commercial peat-based composts, or fertilizer applied to wheat. Garcia-Lil et al. (2000) increased SMBC by 10% to 46% after nine years of application of municipal solid waste (MSW) compost to barley at rates of 20 and 80 t ha^{-1}, respectively. Carter et al. (2004) found no significant difference in SMB-C concentration (μg SMBC g^{-1} soil) where compost was applied at up to 30 t DM ha^{-1}. In grassland systems, the annual flux of N (and P) through the SMB can be greater than recovered in the harvested crop (Lovell et al., 1995). Assuming a mean C:N ratio of 7:1 for SMB under forages (Lovell et al., 1995; Drury et al., 1991) the organic N in SMB in the surface 0-5cm would range from a low of 55 kg N ha^{-1} (N_{high}) to 145 kg N ha^{-1} (DMC300). A consistent relationship between SMB-N content and net N mineralization has proved difficult to establish, however (Paul and Beauchamp, 1996).

When SMBC was expressed as a fraction of SOC (C_{mic}/C_{org} ratio), all fertility treatments, with the exception of N_{high} (2.43% of SOC) and DM300 (4.73% of SOC), failed to differ from the control (4.22% of SOC). Paustian et al. (1992) found the C_{mic}/C_{org} ratio to be higher for plots receiving inputs of farmyard manure (3.1% of SOC) and straw plus N (3.3% of SOC) for 30 years, compared to fertilizer N (2.8% of SOC) or no inputs (2.4% of SOC). High rates of N fertilizer (>200 kg N ha^{-1} y^{-1}) such as applied here, have been found to markedly reduce SMB in grassland soils (Lovell et al., 1995), an effect attributed to the inhibitory effects of large salt concentrations, or relative reductions in sward root mass. Among composts, the lowest proportion of SOC as SMB-C was obtained for SSLC although this treatment produced the highest C_{ext}, and no consistent relationship between C_{ext} and microbial biomass was evident, as reported elsewhere (Gregorich et al., 1998; Chantigny et al., 1999). The CSC compost resulted in a lower C_{mic}/C_{org} ratio at the higher application rate (3.7% when applied at 9.2 Mg C ha^{-1} compared to 4.2% when applied at 4.6 Mg C ha^{-1}) which is attributable to the relative increase in organic matter resistant to microbial attack. A reduction in C_{mic}/C_{org} ratio following higher MSW compost application rates was also reported by Garcia-Lil et al. (2000).

In conclusion, compost use in forage production appears to provide benefits with respect to soil physical and biological properties. Higher quality composts, such as CSC, can evidently sustain grass forage yields, and crop C returns to soil, equivalent to that of inorganic fertilizer. Matching composts of varying quality with the appropriate (legume/non-legume) target crop will be critical to promoting soil C gains from compost use.

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Table 1. Fertility treatments: Total dry matter and carbon applied, and estimated crop derived carbon returns to soil.

Treatment		N application rate (kg N ha^{-1} y^{-1})	Total DM applied (Mg ha^{-1})	Total C applied (Mg ha^{-1})	Estimated crop derived soil C input[c] (Mg ha^{-1})	
					Timothy	Clover-Timothy
Control		-	-	-	4.42	6.00
Fertilizer	Nrec	150 / 40[a]	-	-	6.99	6.20
	Nhigh	300 / 150[a]	-	-	7.24	7.04
Dairy Manure	DM300	300	9.3	2.9[b]	6.22	5.82
Sewage Sludge Compost	SSLC300	300	37.5	10.9	5.42	6.08
Dairy Manure Compost	DMC300	300	25.6	10.0	4.83	6.02
Corn Silage Compost	CSC300	300	11.8	4.6	5.89	6.36
	CSC600	600	23.7	9.2	7.03	7.14

[a] Annual application rates as applied to timothy / timothy and clover forage stands, respectively.
[b] All organic amendments applied by fall of first production year (i.e.fall,1999). [c] Over the period 1998-2000

Table 2. Soil bulk density, carbon concentration, mass and C:N ratio at the 0-5cm depth as affected by crop and fertility treatments in 2000.

Treatment		**Bulk density ($Mg\ m^{-3}$)**	**C concentration** ($g\ C\ kg^{-1}$ soil)	**Total soil C** ($Mg\ C\ ha^{-1}$)	**C:N**
Crop	Clover-Tim.	**1.03** [a]	**40.4** [a]	**20.63** [a]	11.5 [a]
	Timothy	**0.98**	**40.8**	**19.81**	11.7
Fertility	Control	**1.06 a**[b]	**29.3 a**[b]	**15.57 a**[b]	11.1 c[b]
	Nrec	**1.05 ab**	**31.1 a**	**16.23 ab**	11.2 c
	Nhigh	**1.06 a**	**31.8 a**	**16.89 ab**	11.3 cd
	DM300	**1.02 ab**	**35.6 b**	**18.02 b**	11.5 d
	DMC300	**0.97 c**	**52.2 d**	**25.24 d**	**13.0 e**
	SSLC300	**0.90 d**	**53.2 d**	**23.98 d**	**13.9 f**
	CSC300	**1.00 bc**	**41.5 c**	**20.73 c**	**10.6 b**
	CSC600	**1.00 bc**	**50.1 d**	**25.07 d**	**10.2 a**

[a] Values are mean with n=32. Crop x fertility treatment interactions were not significant.

[b] Values are mean with n=8.

Table 3. Soil bulk density, organic carbon concentration, mass and C:N ratio at the 0-5cm depth as affected by fertility treatment in 2001.

Treatment	**Bulk density (Mg m^{-3})**	**Soil C concentration** (g C kg^{-1} soil)	**Total soil C** (Mg C ha^{-1})	C:N
	---------------------------------(0-5cm)---------------------------------			
Control	**0.99 a**[a]	**30.7 a**[a]	**15.22 a**[a]	11.4 b[a]
Nrec	**0.98 a**	**36.6 b**	**17.90 b**	11.5 b
Nhigh	**1.02 a**	**33.0 ab**	**16.72 ab**	11.5 b
DM300	nd[b]	**nd**[b]	nd[b]	nd[b]
DMC300	**0.97 ab**	**51.5 c**	**22.78 c**	12.7 c
SSLC300	**0.79 b**	**57.0 d**	**22.24 c**	**14.2 d**
CSC300	**nd**	**nd**	**nd**	**nd**
CSC600	**0.89 ab**	**54.9 cd**	**24.25 c**	**10.2 a**

[a] Values are mean with n=4.

[b] nd=not determined.

Table 4. Amount, C:N, and ratio of light fraction carbon to total organic carbon at the 0-5cm and 5-10cm depths as affected by crop and fertility treatments in 2000.

Treatment		**LF-C ha^{-1}**	C:N	% SOC
		--------------------(0-5cm)---------------------		
Crop	Clover-Tim.	**4.38** [a]	**18.2** [a]	**18.8 a**[a]
	Timothy	4.40	**19.5**	**20.2 b**
Fertility	Control	1.26 a[b]	**21.2 b**[b]	**8.3 a**[b]
	Nrec	1.63 ab	**19.8 b**	**10.0 a**
	Nhigh	1.92 ab	**19.9 b**	**11.4 ab**
	DM300	2.41 b	**23.0 c**	**13.6 e**
	DMC300	8.80 e	**19.6 b**	**34.1 e**
	SSLC300	7.33 d	**24.6 c**	**29.7 d**
	CSC300	4.11 c	**12.2 a**	**19.3 c**
	CSC600	7.63 d	**10.4 a**	**29.6 d**
		-------------------(5-10cm)-------------------		
Crop	Clover-Tim.	**0.97**	**18.6**	**5.4**
	Timothy	**0.99**	**20.1**	**5.8**
Fertility	Control	**0.90**	**20.2**	**5.5**
	Nrec	**0.73**	**19.4**	**4.5**
	Nhigh	**1.04**	**19.7**	**5.9**
	DM300	0.92	**20.1**	5.4
	DMC300	**0.90**	**19.6**	**5.2**
	SSLC300	**1.08**	**20.6**	**5.9**
	CSC300	**1.05**	**17.8**	**5.9**
	CSC600	**1.16**	**17.0**	**6.0**

[a] Values are mean with n=32. Crop x fertility treatment interactions were not significant.

[b] Values are mean with n=8.

Table 5. Amount, C:N, and ratio of particulate organic carbon to total organic carbon at the 0-5cm depth as affected by fertility treatment (timothy plots only) in 2000.

Treatment		Mg POM-C ha^{-1}	C:N	% SOC
		-----------Fine Sand (53-250µm)-----------		
Fertility	Control	**3.20 a**[a]	12.2 b	21.6
	Nrec	**3.52 ab**	11.9 b	21.8
	Nhigh	**3.09 a**	12.0 b	18.2
	DM300	**nd**[b]	nd	nd
	DMC300	**4.26 b**	12.1 b	17.8
	SSLC300	**4.73 c**	12.8 c	19.3
	CSC300	**3.83 abc**	10.8 a	20.2
	CSC600	**5.33 d**	10.6 a	21.3
		-----Coarse Sand(250-2000µm) -------		
	Control	**2.20 a**[a]	18.2 c	14.8 a
	Nrec	**3.07 a**	16.6 bc	18.9 abc
	Nhigh	**3.34 ab**	16.2 b	19.8 bc
	DM300	**3.23 ab**	17.9 c	17.6 ab
	DMC300	**6.40 d**	17.7 bc	26.9 d
	SSLC300	**8.54 e**	20.7 d	34.8 e
	CSC300	**4.27 b**	12.0 a	22.3 c
	CSC600	**5.97 e**	10.7 a	34.1 e
		------------Litter (250-2000µm)----------		
	Control	**0.34 a**[a]	26.9 bd	2.3 a
	Nrec	**0.54 a**	27.3 bcd	3.3 a
	Nhigh	**0.66 a**	23.9 b	3.9 a
	DM300	**0.69 a**	33.1 d	3.8 a
	DMC300	**3.27 c**	24.4 b	13.5 c
	SSLC300	**3.03 c**	32.0 cd	12.4 c
	CSC300	**0.84 a**	15.4 a	4.4 a
	CSC600	1.92 b	10.8 a	7.6 b

[b] Values are mean with n=4.

[b]nd=not determined.

Table 6. Amount of available carbon and soil microbial biomass carbon, and their ratio to total organic carbon at the 0-5cm and 5-10cm depth affected by crop and fertility treatment in 2000.

Treatment		Soil microbial biomass (SMB)		Available carbon (C_{ext})[a]	
		µg SMB-C (g soil)$^{-1}$	% SOC	**µg C_{ext}-C** (g soil)$^{-1}$	% SOC
		--------------------------------(0-5cm)--------------------------------			
Crop	Clover-Tim.	1169.3 [b]	3.1 [b]	60.4	0.16 [b]
	Timothy	1741.8	4.3	71.5	0.18
Fertility	Control	1255.8 ab[c]	4.2 bc[c]	56.3 a	0.19 bc[c]
	Nrec	945.7 a	3.0 ab	63.1 a	0.20 c
	Nhigh	757.0 a	2.4 a	66.1 a	0.21 c
	DM300	1653.5 ac	4.7 c	63.4 a	0.18 bc
	DMC300	2125.0 c	4.1 bc	80.6 b	0.16 ab
	SSLC300	1721.3 bc	3.2 ab	83.2 b	0.16 ab
	CSC300	1737.6 bc	4.2 bc	56.6 a	0.14 a
	CSC600	1868.4 c	3.7 bc	58.2 a	0.12 a
		-------------------------------(5-10cm)--------------------------------			
Crop	Clover-Tim.	562.8	1.9	57.2	0.19
	Timothy	558.5	1.9	58.4	0.20
Fertility	Control	561.7	2.2	54.2 ab	0.20
	Nrec	nd[d]	nd[d]	nd[d]	nd[d]
	Nhigh	566.1	2.0	48.1 a	0.17
	DM300	608.0	2.1	62.4 bc	0.21
	DMC300	566.6	1.9	58.7 bc	0.19
	SSLC300	524.1	1.7	66.5 c	0.21
	CSC300	nd	nd	nd	nd
	CSC600	538.1	1.7	57.2 b	0.21

[a] Extracted with 0.5 M K_2S0_4.

[b] Values are mean with n=32. Crop x fertility treatment interactions were not significant.

[c] Values are mean with n=8

[d] nd=not determined.