Pedobiologia **49** (2005) 283—296

Available online at www.sciencedirect.com

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Pedobiologia

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Distinguishing urban soils with physical, chemical, and biological properties

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Received 19 August 2004; accepted 22 December 2004

KEYWORDS
Urban soil;
Bulk density;
Particulate organic matter;
Nitrogen mineralization;
Microbial biomass and activity

Summary

Modifications associated with urban infrastructure directly impact soil properties. In particular, soil bulk density, microbial biomass and activity, and organic matter are impacted by anthropogenic activities. We proposed that urban soil properties are not only distinguishable from other systems, but also variable within types of landscapes in urban environments. We found soils from older urban landscapes (mean landscape age of 64 years) to be distinct from newer urban landscapes (mean landscape age of 9 years). Soil bulk densities were significantly greater in newer (1.73 g cm^{-3}) compared to older urban soils (1.41 g cm^{-3}). Older urban soils had significantly greater extractable phosphorous, weak Bray P (24%), strong Bray P (51%), and K (45%) than newer urban soils. Soil biological measures of nitrogen availability were significantly greater in old compared to new urban soils, microbial biomass N (71%), potential C mineralization (20%), and potential N mineralization (83%). We found exponentially decreasing metabolic quotient values, qCO_2, suggesting the impact of site disturbance decreases rapidly with time, and older urban landscapes are closer to steady-state conditions relative to younger urban landscapes. Total soil organic matter was significantly greater (35%) in old urban soils. Fine POM was a larger contributor to total SOM in old compared to new urban soils. Particulate organic matter C/N ratios from older urban soils were less (coarse POM 14% less and fine POM 13% less) than newer urban soils. Of the soil forming factors, time played the most significant role in soil

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doi:10.1016/j.pedobi.2004.12.002

physical, chemical, and biological differences. We believe that as time since initial disturbance increases, the impacts of urbanization are reduced by processes improving physical, biological, and chemical soil properties.
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Introduction

Soils are dramatically altered by human activities in urban environments and these alterations distinguish these soils from those in other systems and within urban environments (Craul, 1999). Research has assessed the unique physical, biological, and chemical properties of urban soils. Specifically, urban soil bulk density (Short et al., 1986a, b; Jim, 1998a–c), soil microbial biomass and activity (White and McDonnell, 1988; Carreiro et al., 1999; Zhu and Carreiro, 1999), and soil organic matter quantity and quality (Beyer et al., 1995, 1996; Pouyat et al., 2002) have been studied and found to be affected by urban conditions.

Physical soil modification is necessary for infrastructure. Road engineering requires packing soils to high bulk densities for load-bearing (Grabosky and Bassuk, 1995). Soil texture amendments, heavy equipment, foot traffic, and covering surfaces with hard-space all reduce aggregation and apply external forces that exceed the soil shear strength resulting in ped breakdown, pore collapse, and dense particle packing (Jim, 1998b). Many studies have measured high bulk densities in urban soils (Short et al., 1986a, b; Jim, 1998a–c). In Hong Kong, Jim (1998a) found two-thirds of sampled soils with bulk density values exceeding $1.6\,g\,cm^{-3}$, which is considered the upper threshold for unimpaired root growth (Mullins, 1991). But, substantially lower urban soil bulk densities (e.g., $<1.0\,g\,cm^{-3}$) have also been measured (Strain and Evans, 1994), which is evidence of the spatial variability of soils in urban environments.

Soil biological properties in urban environments also vary and differ from those in other managed and natural systems (White and McDonnell, 1988; Goldman et al., 1995; Pouyat et al., 1995; Carreiro et al., 1999). White and McDonnell (1988) found significantly lower net nitrogen mineralization rates in the urban forest floor and A horizons (81% and 53%, respectively) than in comparable rural soils. Carreiro et al. (1999) found soil decomposition to be reduced by 25% and microbial biomass by 50% in urban compared to rural soils. Conversely, increased nitrification rates have been found in urban compared to rural soils (Zhu and Carreiro, 1999).

Soil microbial parameters, such as microbial carbon to total organic carbon (C_{mic}/TOC) or basal respiration to microbial biomass (metabolic quotient, qCO_2), are reliable indicators for describing changes in ecosystems (Insam and Domsch, 1988; Insam and Haselwandter, 1989; Insam et al., 1989). The ratio of C_{mic}/TOC indicates the proportion of carbon that may be readily metabolized. The qCO_2 identifies the metabolically active portion of the microbial community (Anderson and Domsch, 1989, 1990). Disturbance generally produces an initial decrease in TOC and C_{mic}, and respiration (Kieft et al., 1998). The C_{mic}/TOC and qCO_2 tend to increase immediately following disturbance and then to decrease gradually following recovery. Increases in these ratios are indicative of organic matter losses, decreases indicate organic matter accumulation, and steady-state values are indicative of climax communities (Insam and Haselwandter, 1989). Beyer et al. (1995) found higher C_{mic}/TOC and the qCO_2 values for younger urban soils indicative of early soil development. Although important for examining soil biological and organic matter dynamics, these microbial parameters have been rarely studied in urban soils (Beyer et al., 1995).

The quantity and quality of urban soil organic matter is quite variable (Beyer et al., 1996; Carreiro et al., 1999; Pouyat et al., 2002). In preparation for infrastructure topsoil is removed, leading to reductions in soil organic matter (Pulford, 1991; Craul, 1993; Harris et al., 1999). The removal of grass clippings, tree leaves, and other organic debris can further reduce inputs to the soil organic matter pool; while, organic additions such as top soil replacement, mulch, root turnover, microbes, earthworms, grass clippings, and leaf litter left on site help to build soil organic matter (Craul, 1999). Studies of urban soils often describe decreased organic matter contents compared to soils of other systems (Cotrufo et al., 1995; Zhu and Carreiro, 1999). Organic matter contents in urban soils were less than 1%, compared to forested soils with 4–5%, and some agricultural soils with as much as 10% soil organic matter (Craul, 1993; Jim, 1998a). In contrast, organic matter quantities have been measured in urban soils that are substantially higher than in other non-urban soils (White and McDonnell, 1988; Pouyat et al.,

1995, 2002). Pouyat et al. (2002) described urban soils with significantly higher organic carbon densities, 97 g kg^{-1}, than suburban, 83 g kg^{-1} and rural soils, 73 g kg^{-1}.

Most research of urban soil organic matter has been quantitative, but qualitative differences have also been measured (Beyer et al., 1995, 1996). Certain portions of soil organic matter are more labile than other more recalcitrant fractions. Particulate organic matter (POM) has been identified as soil organic matter more actively involved in decomposition and mineralization processes (Elliot and Cambardella, 1991; Magid et al., 1996; Six et al., 2002). Although POM is known to be indicative of soil organic matter quality, no research has examined POM in urban soils.

The goal of our study was to emphasize and explain spatial variability in urban soils. We attempt this by measuring physical, chemical, and biological properties of soils in an array of urban landscapes. We then relate these properties to soil processes and forming factors to solicit differences in the soil development in various urban landscapes. The research database on soil development in urban soils is minimal, and we hope to contribute knowledge to this growing area of interest.

Materials and methods

Study sites were selected within the cities of Moscow, Idaho, 46°44′N and 116°58′W and Pullman, Washington, 46°43′N and 117°11′W. Human population density in Moscow, ID is 882 people km^{-2} and 1069 people km^{-2} in Pullman, WA. The soils are described as Palouse silt loam (fine-silty, mixed, mesic, Pachic Ultic Haploxerolls) with 7–25% slopes (USDA Soil Survey of Whitman County, Washington, 1980; USDA Soil Survey of Latah County, Idaho, 1981). The soils were formed in loess and volcanic ash and are well to moderately well-drained. The sample region is gently sloping to moderately steep silt loam on uplands. The elevation is approximately 790 m. The average annual precipitation is 530–840 mm and the average frost-free season is 90–140 days. During 2002 and 2003, the mean air temperature was 12.1 °C and the temperature in the top 10 cm of soil was approximately 10.1 °C (Patten, 2003). The average amount of precipitation for 2002 and 2003 was 76 cm, with the majority as snow (Patten, 2003).

The urban landscapes included residential yards greater than 50 years old, residential yards less than 10 years old, mulched beds greater than 10 years old, mulched beds less than 3 years old, street tree plantings, and parks (Table 1). Two deciduous tree sites were nested within four locations of each of the six urban landscape types, for a total of 48 urban sites. Site, vegetation, and soil management history were attained for each site by personal interviews. Management practices such as fertilization, irrigation, mulching, and lawn care were monitored for data interpretation.

Soil samples were collected throughout two growing seasons, 9 times in 2002 and 7 times in 2003. In 2002, sampling occurred on 04/17, 05/01, 05/15, 05/29, 06/12, 06/26, 08/03, 09/05, and 10/03. In 2003, soils were sampled on 04/11, 05/09, 06/13, 07/11, 08/08, 09/12, and 10/10. Six 2.5 cm diameter by 15 cm deep cores were taken from each site on each sample date. Soils were passed through a 6 mm wire screen to remove stones and organic debris while minimizing the impact on biological measurements (Ross, 1992). After sieving, soil samples were stored at 4 °C until processed.

Soil bulk density was determined from soils collected on 04/17/02 and reported as g cm^{-3}. Soil textural analysis was performed by Midwest Laboratories Inc., Omaha, NE, with soils collected on 04/17/02. Gravimetric soil moisture content was determined by drying samples at 105 °C for 24 h to determine dry soil weight. Soil sub-samples were adjusted to 40% water holding capacity for further chemical and biological analysis (Kaiser et al., 1992; Joergensen and Mueller, 1996).

Soil respiration, expressed as potentially mineralizable carbon (PMC) was measured with 20-day soil incubations using NaOH traps. Carbon dioxide sequestered in NaOH was precipitated with $BaCl_2$ followed by 0.25 M, unstandardized, HCl titration to a phenolphthalein endpoint (Anderson and Domsch, 1978; Parkin et al., 1996). Potentially mineralizable nitrogen (PMN) was determined with 20-day aerobic incubations followed by nitrogen extractions with 0.5 M K_2SO_4 and colorimetric analyses (Drinkwater et al., 1996). Mineral nitrogen (NH_4^+, NO_2^-, and NO_3^-) prior to incubation was subtracted from nitrogen mineralized during the 20 days. PMN and carbon were expressed as rates of μg N or CO_2 mineralized g^{-1} day^{-1}.

A modification of the soil fumigation-extraction method (Brookes et al., 1985; Sparling et al., 1990; Cabrera and Beare, 1993) was used to determine microbial biomass nitrogen (MBN). Soil samples were fumigated with ethanol-free chloroform for 5 days, extracted with 0.5 M K_2SO_4, and extractable nitrogen was reduced to NH_4^+ for colorimetric analysis at 650 nm. MBN was the difference in nitrogen between the fumigated and the unfumigated samples, using an extraction efficiency

Table 1. Description of site, tree, and maintenance activities on six urban landscapes studied throughout the 2002 and 2003 growing seasons in Moscow, ID and Pullman, WA

Landscape type	Location	Age (yr)	Genus species	Height (m)	**Dbh (cm)**	Fertilization (NPK) broadcast yr^{-1}	Irrigation		Lawn mowing		Mulch		
							# wk^{-1}	Type	# wk^{-1}	Clippings	cm	Type	Matting
NRL	Moscow, ID	5	*Carpinus caroliniana*	3	5	2	7–14	Underground	1–2	Often removed		N/A	
NRL	Moscow, ID	5	*Quercus rubra*	5	8	2	7–14	Underground	1–2	Often removed		N/A	
NRL	Moscow, ID	4	*Acer rubrum*	2	5	2	7–14	Underground	1–2	Mulch mow		N/A	
NRL	Moscow, ID	4	*Betula nigra*	4	7	2	7–14	Underground	1–2	Mulch mow		N/A	
NRL	Pullman, WA	4	*Acer platanoides*	3	6	2	7–14	Underground	1–2	Often removed		N/A	
NRL	Pullman, WA	4	*Acer platanoides*	3	6	2	7–14	Underground	1–2	Often removed		N/A	
NRL	Pullman, WA	3	*Acer platanoides*	3	6	2	7–14	Underground	1–2	Mulch mow		N/A	
NRL	Pullman, WA	3	*Acer platanoides*	3	5	2	7–14	Underground	1–2	Mulch mow		N/A	
ORL	Moscow, ID	57	*Aesculus hippocastanum*	20	70	0–1	1–14	Sprinkler	1	Mulch mow		N/A	
ORL	Moscow, ID	57	*Tilia americana*	16	60	0–1	1–14	Sprinkler	1	Mulch mow		N/A	
ORL	Moscow, ID	61	*Crataegus* spp.	10	45	0–1	1–14	Sprinkler	1	Often removed		N/A	
ORL	Moscow, ID	61	*Crataegus* spp.	10	48	0–1	1–14	Sprinkler	1	Often removed		N/A	
ORL	Pullman, WA	63	*Juglans nigra*	20	75	0–1	1–14	Underground	1	Often removed		N/A	
ORL	Pullman, WA	63	*Juglans nigra*	20	73	0–1	1–14	Underground	1	Often removed		N/A	
ORL	Pullman, WA	62	*Populus deltoides*	24	85	0–1	1–14	Sprinkler	1	Mulch mow		N/A	
ORL	Pullman, WA	62	*Populus deltoides*	24	85	0–1	1–14	Sprinkler	1	Mulch mow		N/A	
PAL	Moscow, ID	102	*Tilia americana*	15	56	2	1–14	Sprinkler	1	Mulch mow		N/A	
PAL	Moscow, ID	102	*Tilia americana*	15	55	2	1–14	Sprinkler	1	Mulch mow		N/A	
PAL	Moscow, ID	52	*Acer saccharinum*	25	85	2	1–14	Sprinkler	1	Mulch mow		N/A	
PAL	Moscow, ID	52	*Acer rubrum*	10	50	2	1–14	Sprinkler	1	Mulch mow		N/A	
PAL	Pullman, WA	82	*Fraxinus pennsylvanica*	12	46	1	1–14	Underground	1	Mulch mow		N/A	
PAL	Pullman, WA	82	*Acer platanoides*	13	50	1	1–14	Underground	1	Mulch mow		N/A	

PAL	Pullman, WA	102	*Ulmus americana*	26	87	1	1–14	Underground	1	Mulch mow		N/A	
PAL	Pullman, WA	102	*Aesculus hippocastanum*	23	77	1	1–14	Underground	1	Mulch mow		N/A	
STL	Moscow, ID	35	*Acer platanoides*	15	58	0–1	0–7	Sprinkler	1	Mulch mow		N/A	
STL	Moscow, ID	35	*Acer platanoides*	15	55	0–1	0–7	Sprinkler	1	Mulch mow		N/A	
STL	Moscow, ID	60	*Acer platanoides*	20	63	0–1	0–7	Underground	1	Mulch mow		N/A	
STL	Moscow, ID	60	*Acer platanoides*	20	66	0–1	0–7	Underground	1	Mulch mow		N/A	
STL	Moscow, ID	60	*Acer platanoides*	20	65	0–1	0–7	Sprinkler	1	Mulch mow		N/A	
STL	Moscow, ID	60	*Acer platanoides*	20	68	0–1	0–7	Sprinkler	1	Mulch mow		N/A	
STL	Moscow, ID	30	*Fraxinus pennsylvanica*	10	40	0–1	0–7	Underground	1	Mulch mow		N/A	
STL	Moscow, ID	30	*Fraxinus pennsylvanica*	10	38	0–1	0–7	Underground	1	Mulch mow		N/A	
NML	Moscow, ID	6	*Fraxinus pennsylvanica*	3	5	None	7–14	Underground		N/A	6	Pine-fir	Yes
NML	Moscow, ID	6	*Fraxinus pennsylvanica*	3	5	None	7–14	Underground		N/A	6	Pine-fir	Yes
NML	Moscow, ID	2	*Fraxinus pennsylvanica*	3	5	None	7–14	Underground		N/A	10	Pine-fir	No
NML	Moscow, ID	2	*Fraxinus pennsylvanica*	3	5	None	7–14	Underground		N/A	10	Pine-fir	No
NML	Moscow, ID	1	*Acer platanoides*	2	4	None	7–14	Underground		N/A	8	Pine-fir	No
NML	Moscow, ID	1	*Acer platanoides*	2	4	None	7–14	Underground		N/A	8	Pine-fir	No
NML	Moscow, ID	2	*Gleditsia triacanthos*	3	5	None	7–14	Underground		N/A	7	Pine-fir	Yes
NML	Moscow, ID	2	*Gleditsia triacanthos*	3	5	None	7–14	Underground		N/A	7	Pine-fir	Yes
OML	Moscow, ID	15	*Celtis occidentalis*	7	12	None	7–14	Underground		N/A	5	Pine-fir	Yes
OML	Moscow, ID	15	*Celtis occidentalis*	7	12	None	7–14	Underground		N/A	5	Pine-fir	Yes
OML	Moscow, ID	20	*Acer platanoides*	7	15	None	7–14	Underground		N/A	3	Pine-fir	No
OML	Moscow, ID	20	*Acer platanoides*	7	14	None	7–14	Underground		N/A	3	Pine-fir	No
OML	Moscow, ID	20	*Quercus rubra*	7	14	None	7–14	Underground		N/A	10	Pine-fir	Yes
OML	Moscow, ID	20	*Quercus rubra*	7	16	None	7–14	Underground		N/A	10	Pine-fir	Yes
OML	Moscow, ID	20	*Crataegus* spp.	7	15	None	7–14	Underground		N/A	5	Pine-fir	No
OML	Moscow, ID	20	*Crataegus* spp.	7	14	None	7–14	Underground		N/A	5	Pine-fir	No

Street tree, STL; park, PAL; old residential, ORL; old mulch, OML; new residential, NRL; and new mulch urban landscapes, NML.

factor of $K_{EN} = 0.54$ (Joergensen and Mueller, 1996). MBN was expressed as $\mu g\,N\,g^{-1}$. Microbial biomass carbon (MBC) was calculated from measured MBN values, assuming 8/1 microbial C/N ratio (Brady and Weil, 2002). MBC was then used to calculate the metabolic quotient, (mg CO_2 evolved $h^{-1}\,g^{-1}$/mg MBC g^{-1}) and microbial to total organic carbon ratios (μg MBC g^{-1}/mg TOC g^{-1}).

Soil samples collected at the beginning and end of each growing season (04/17/02, 10/03/02, 04/11/03, and 10/10/03) were analyzed for pH in water (1:1), cation exchange capacity in $\mu mol_C\,g^{-1}$; extractable weak Bray phosphorous, strong Bray phosphorous, and potassium in $\mu g\,g^{-1}$ (Midwest Laboratories Inc., Omaha, NE). On all sample dates, mineral nitrogen (MIN) and dissolved organic nitrogen (DON) was determined by extraction with 0.5 M K_2SO_4, followed by colorimetric analyses at 650 nm for ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) (Sims et al., 1995). Ammonium concentrations in filtrate extracts were measured, and a reduction with Devarda's alloy and sulfuric acid was used to reduce NH_4^+ to nitrite and nitrate. MIN was NH_4^++NO_2^-+NO_3^- in extracts. Alkaline persulfate digestion under pressure was used to determine total nitrogen in filtrate extracts. The difference between total extractable nitrogen and MIN was DON, expressed as $\mu g\,g^{-1}$.

Total soil organic matter was determined by the Walkley–Black method with samples collected on 04/17/02, 10/03/02, 04/11/03, and 10/10/03 (Midwest Laboratories, Inc., Omaha, NE). Total soil organic matter was also determined by loss on ignition (LOI) on all dates (Schulte et al., 1991; Sikora and Stott, 1996). To compute the MBC/TOC ratio, total organic carbon (TOC) was related from soil organic matter. TOC was determined by multiplying the average of the two soil organic matter measurements by 0.5 (Brady and Weil, 2002).

POM fractions were isolated by particle size fractionation (Elliot and Cambardella, 1991; Cambardella and Elloitt, 1992, 1993; Six et al., 2002). Soil samples were shaken for 15 h with sodium hexametaphosphate ($NaPO_3$) and then passed through a series of nested sieves. Litter soil organic matter was collected on the 2000 μm sieve. Coarse POM (cPOM) was collected on the 250 μm sieve. Fine POM (fPOM) was collected on the 53 μm sieve. Mineral-associated soil organic matter, which went through the 53 μm sieve, was determined by subtraction of the litter SOM, cPOM, and fPOM from total SOM.

LOI and automated dry combustion methods were used to determine organic matter, nitrogen, and carbon in each size fraction. Once fractionated, samples were oven dried at 105 °C, homogenized, and weighed. Sub-samples of the coarse and fine POM fractions were analyzed for total nitrogen and carbon content by dry combustion with an automated gas combustion analyzer (Vario Max CNS, Elementar). Nitrogen and carbon in the POM fractions (cPOM N, cPOM C, fPOM N, and fPOM C) were expressed as C/N ratios of those fractions. The remaining portions of the litter SOM, cPOM, and fPOM fractions were dried at 105 °C and burned at 360 °C for 6 h to determine ash weight by LOI (Schulte et al., 1991; Sikora and Stott, 1996). Soil organic matter in litter SOM, cPOM, fPOM, and mineral associated SOM was expressed as kg SOM m^{-2} 15 cm^{-1} in that fraction.

The experiment was a repeated measure over time with a nested whole plot structure. Repeated measures analysis of variance (ANOVA) and the general linear model procedure were used with Fisher's protected LSD to detect seasonal changes and significant differences ($p \leqslant 0.05$) among the urban landscapes (SAS, 1999). Linear regression analyses were performed to investigate soil correlations ($p \leqslant 0.05$) among measured soil parameters (SAS, 1999).

Results

All soils were classified as silt loam (Table 2). The urban landscapes did not differ in silt, but clay contents were significantly greater on new residen-

Table 2. Soil bulk density and texture from six urban landscapes in Moscow, ID and Pullman, WA in 2002

	D_b (g cm^{-3})	Texture class	Sand (%)	Silt (%)	Clay (%)
NML	1.55 abc	Silt loam	18.5 bc	58.3 a	23.3 a
NRL	1.73 a	Silt loam	17.3 c	61.8 a	21.0 a
OML	1.59 ab	Silt loam	18.3 bc	62.5 a	19.3 a
ORL	1.41 bc	Silt loam	27.0 ab	61.0 a	12.0 b
PAL	1.39 c	Silt loam	26.5 ab	62.5 a	11.0 b
STL	1.39 c	Silt loam	30.5 a	56.6 a	13.0 b

Means with same letter are not significantly different at $p \leqslant 0.05$.

tial (21.0%) and mulched (23.3% and 19.3%) sites compared to old residential (12.0%), street (13.0%), and park (11.0%) sites. New residential (17.3%) sites had significantly lower sand contents compared to old residential (27.0%), park (26.5%), and street (30.5%) sites. Sand contents on mulched (18.5% and 18.3%) sites tended to be closer to those on new residential sites. Soil bulk density was significantly greater on new residential sites ($1.73\,g\,cm^{-3}$) compared to old residential ($1.41\,g\,cm^{-3}$), street ($1.39\,g\,cm^{-3}$), and park sites ($1.39\,g\,cm^{-3}$). Soil bulk densities were significantly greater on old mulch ($1.59\,g\,cm^{-3}$) and new mulch sites ($1.55\,g\,cm^{-3}$) compared to park and street sites (Table 2). On all urban landscapes, gravimetric soil moisture contents were greatest on 04/17/02 (20.7–25.7%) and on 04/11/03 (20.2–25.7%) and declined throughout the remainder of the growing seasons (decreases of 12–24%) ($p \leqslant 0.0001$). Seasonal mean moisture values were significantly greater on new mulch sites (24.8% and 21.7%) and lowest on street sites (14.4% and 14.6%) compared to other urban landscapes (Table 3).

Significant time and time by treatment effects for microbial biomass N were observed in 2002 and 2003 ($p \leqslant 0.0001$) (Fig. 1). Microbial biomass N was significantly greater from park, street, and old residential sites, when compared to old mulch, new mulch, and new residential sites on all 2002 and 2003 sample dates ($p \leqslant 0.0001$). The time by treatment interactions for MBN were orderly, i.e., landscape differences were temporally consistent; thus tests of main treatment effects with seasonal mean data were performed for urban landscape comparisons (Table 3). The 2002 and 2003 seasonal mean MBN values for park (52.2 and $60.5\,\mu g\,g^{-1}$), old residential (51.1 and $54.0\,\mu g\,g^{-1}$), and street sites (39.7 and $42.9\,\mu g\,g^{-1}$) were significantly greater than new residential (14.0 and $16.5\,\mu g\,g^{-1}$), old mulch (16.9 and $13.0\,\mu g\,g^{-1}$) and new mulch sites (14.1 and $10.2\,\mu g\,g^{-1}$).

Time significantly impacted potential carbon mineralization ($p \leqslant 0.0001$) (Fig. 1). Large PMC values were observed on all urban landscapes on 08/07/02 (45.1–55.4 $\mu g\,CO_2\,g^{-1}\,d^{-1}$), and 08/08/03 (20.2–33.0 $\mu g\,CO_2\,g^{-1}\,d^{-1}$). The treatment effects for PMC were significant ($p \leqslant 0.037$) throughout both growing seasons, and the time by treatment interactions ($p \leqslant 0.0001$) were orderly. The 2002 and 2003 seasonal mean values for PMC were significantly greater on park sites (20.7 and $18.0\,\mu g\,g^{-1}\,d^{-1}$), street (19.1 and $19.7\,\mu g\,g^{-1}\,d^{-1}$), old residential (19.6 and $17.9\,\mu g\,g^{-1}\,d^{-1}$), new mulch (23.6 and $17.8\,\mu g\,g^{-1}\,d^{-1}$) compared to old mulch sites (12.5 and $9.9\,\mu g\,g^{-1}\,d^{-1}$) (Table 3). Potential C mineralization values from new residential sites (14.8 and $15.2\,\mu g\,g^{-1}\,d^{-1}$) tended to be greater than old mulch sites but less than those from all other urban landscapes.

Table 3. Means values of soil nutrients and associated measurements from six urban landscapes in Moscow, ID and Pullman, WA in 2002 and 2003

GSM (%)	pH (1:1)	CEC ($\mu mol_C\,g^{-1}$)	$\mu g\,g^{-1}$					$\mu g\,C$ or $N\,g^{-1}$		$\mu g\,C$ or $N\,g^{-1}\,day^{-1}$	
			P_{wB}	P_{sB}	K	MIN[a]	DON[a]	MBC[b]	MBN	PMC	PMN[c]
2002											
NML 24.8 a	6.91 a	11.4 cd	96.3 a	143.3 a	254. 5 bc	10.3 a	3.0 a	112.9 c	14.1 c	23.6 a	0.38 cd
NRL 19.0 b	7.08 a	12.1 bcd	23.3 b	59.3 b	158.2 c	8.0 a	1.2 ab	112.0 c	14.0 c	14.8 bc	0.13 d
OML 19.2 b	6.64 a	13.0 abc	49.8 ab	114.3 ab	251.1 bc	5.2 a	1.3 ab	135.2 c	16.9 c	12.5 c	0.50 bc
ORL 18.4 b	6.93 a	13.6 a	36.7 ab	132.4 ab	328.3 ab	5.9 a	1.9 ab	408.5 a	51.1 a	19.6 ab	0.60 bc
PAL 20.6 b	6.73 a	13.3 ab	60.1 ab	166.0 a	425.7 a	9.4 a	2.3 ab	417.6 a	52.2 a	20.7 a	1.01 a
STL 14.4 c	6.61 a	11.1 d	65.6 ab	152.6 a	443.6 a	10.0 a	0.8 b	317.9 b	39.7 b	19.1 ab	0.71 b
2003											
NML 21.7 a	6.81 ab	14.7 bc	95.3 a	147.9 a	338.9 bc	6.0 a	1.7 a	81.6 c	10.2 c	17.8 a	0.15 cd
NRL 17.7 b	7.32 a	17.2 a	31.8 b	64.0 b	243.9 c	4.4 a	2.0 a	131.7 c	16.5 c	15.2 ab	0.03 d
OML 17.8 b	6.76 b	16.4 ab	42.6 ab	101.7 ab	333.8 bc	4.6 a	2.1 a	104.3 c	13.0 c	9.9 b	0.18 cd
ORL 18.9 b	7.01 ab	16.6 ab	36.3 ab	121.3 ab	398.4 ab	5.8 a	2.3 a	432.3 ab	54.0 ab	17.9 a	0.34 bc
PAL 20.8 ab	6.87 ab	16.0 ab	59.6 ab	144.4 a	523.9 a	7.8 a	2.1 a	484.1 a	60.5 a	18.0 a	0.67 a
STL 14.6 c	6.69 b	13.5 c	68.8 ab	160.6 a	503.6 a	7.5 a	1.8 a	342.8 b	42.9 b	19.7 a	0.56 ab

Means with same letter are not significantly different at $p \leqslant 0.05$.

[a]Means of mineral and dissolved organic nitrogen are given but time effect confounded landscape differences.

[b]Microbial biomass carbon calculated from microbial biomass nitrogen.

[c]Potential nitrogen immobilization in OML (09/12/03), NML (09/05/02, 10/03/02, 06/13/03, 09/12/03), and NRL (05/15/02, 05/29/02, 06/12/02, 09/05/02, 10/03/02, 06/13/03, 08/08/03, 09/12/03, 10/10/03).

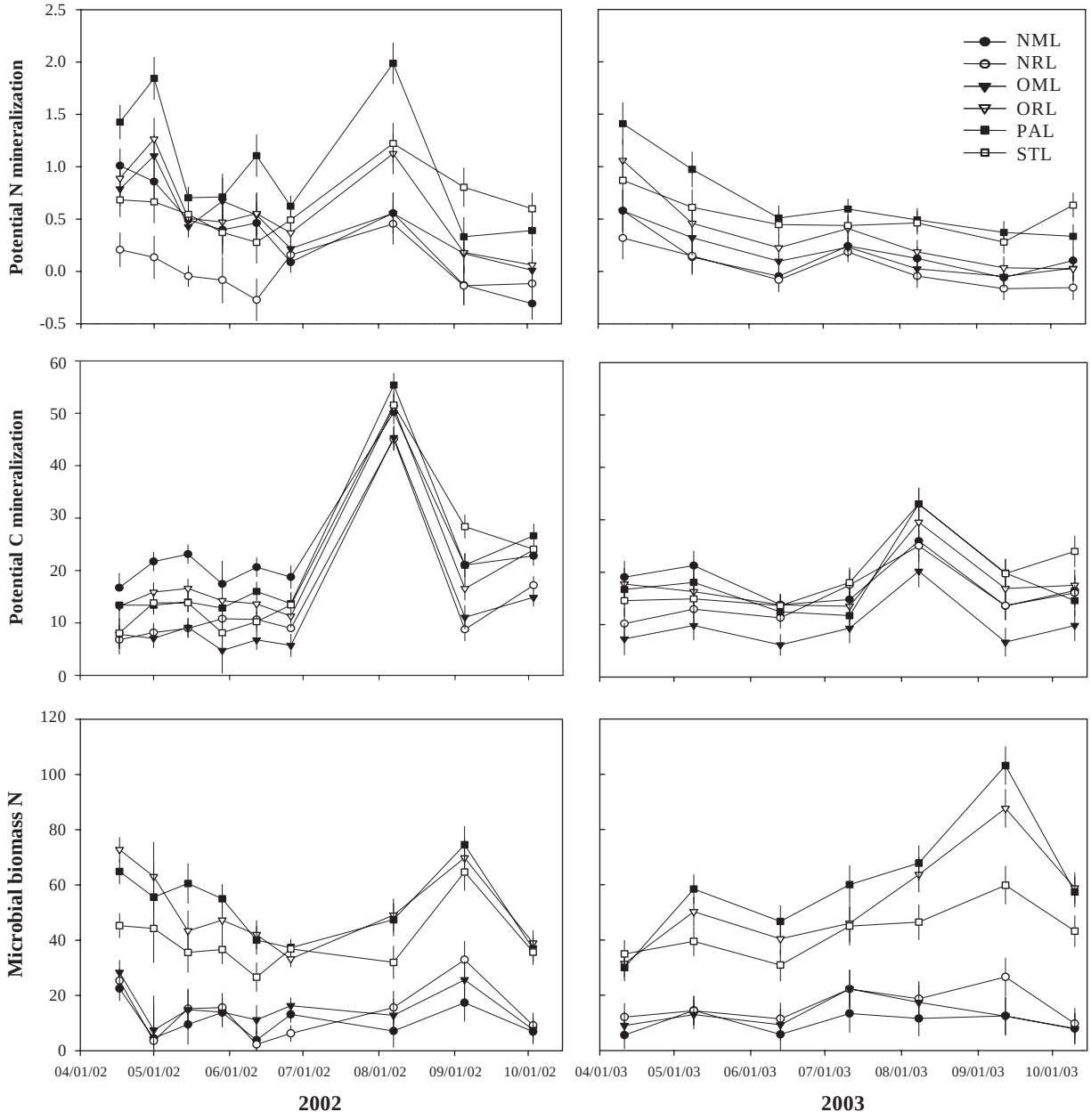

Figure 1. Seasonal changes of extractable mineral and DON, potential nitrogen and carbon mineralization, and MBN throughout the 2002 and 2003 growing seasons from six urban landscapes in Moscow, ID and Pullman, WA. Street tree, STL; park, PAL; old residential, ORL; old mulch, OML; new residential, NRL; and new mulch urban landscapes, NML. Extractable mineral nitrogen, MIN, and dissolved organic nitrogen, DON, are $\mu g\, g^{-1}$. Potential nitrogen mineralization, PMN, is μg N mineralized $g^{-1}\, day^{-1}$. Potential carbon mineralization, PMC, is μg of CO_2 evolved $g^{-1}\, day^{-1}$. Microbial biomass nitrogen, MBN, is $\mu g\, N\, g^{-1}$ of nitrogen in microbial biomass. Standard error bars separate mean values on each date.

Significant treatment, time, and time by treatment effects for potential N mineralization were observed in 2002 and 2003 ($p \leqslant 0.0001$). The time by treatment interactions for potential nitrogen mineralization were orderly. Seasonal mean PMN values on park (1.01 and $0.67\, \mu g\, g^{-1}\, d^{-1}$), old residential (0.60 and $0.34\, \mu g\, g^{-1}\, d^{-1}$), and street (0.71 and $0.56\, \mu g\, g^{-1}\, d^{-1}$) sites were significantly greater than on new residential sites (0.13 and $0.03\, \mu g\, g^{-1}\, d^{-1}$) (Table 3). Due to a large (59–85%) late season increase observed on 08/07/02, PMN 2002 means tended to be greater than PMN means in 2003. Potential N mineralization on new mulch (0.38 and $0.15\, \mu g\, g^{-1}\, d^{-1}$) and old mulch sites (0.50 and $0.18\, \mu g\, g^{-1}\, d^{-1}$) tended to fall between these extremes. Negative values of PMN, indicative of

nitrogen immobilization were measured in soils from old mulch sites (09/12/03), new mulch sites (09/05/02, 10/03/02, 06/13/03, and 09/12/03), and new residential sites (05/15/02, 05/29/02, 06/12/02, 09/05/02, 10/03/02, 06/13/03, 08/08/03, 09/12/03, and 10/10/03) (Fig. 1).

Metabolic quotients (qCO_2) tended to decrease exponentially with increasing urban landscape age ($R^2 = 0.92$) (Fig. 2). Metabolic quotients on park, street, and old residential sites were less than those from new residential and mulched sites. Ratios of microbial to organic carbon (MBC/TOC) tended to be higher on old residential, park, and street sites compared to new residential and mulched sites.

Soil pH values were between 6 and 7, with minimal differences among urban landscapes (Table 3). Soil cation exchange capacity tended to be less on street and new mulch landscapes ($12.7\,\mu mol_C\,g^{-1}$) than other sites ($14.8\,\mu mol_C\,g^{-1}$) (Table 3). Soil phosphorous, weak and strong Bray, was lowest on new residential sites (27.6 and $61.7\,\mu g\,g^{-1}$) and higher on park, street, and new mulch sites (74.3 and $152.5\,\mu g\,g^{-1}$) (Table 3). Soil potassium was lower on new residential sites ($201.1\,\mu g\,g^{-1}$) and higher on park and street sites ($474.2\,\mu g\,g^{-1}$) (Table 3).

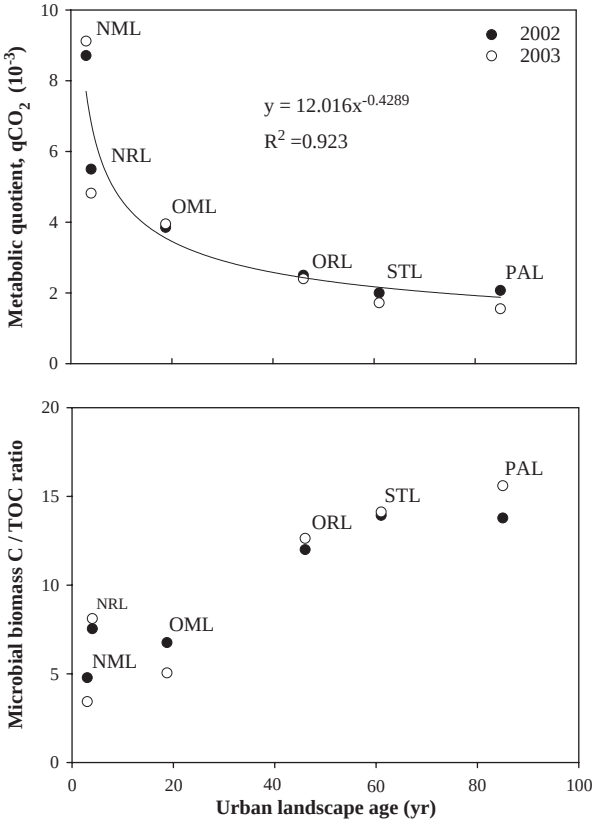

Figure 2. Metabolic quotient and microbial biomass to TOC ratios from six urban landscapes in Moscow, ID and Pullman, WA from 2002 and 2003. Street tree, STL; park, PAL; old residential, ORL; old mulch, OML; new residential, NRL; and new mulch urban landscapes, NML.

Compared to other soil measurements, extractable mineral N was temporally and spatially erratic throughout the 2002 and 2003 growing seasons (time, time by treatment interaction; $p \leqslant 0.0001$). Urban landscape MIN differences ($p > 0.303-0.483$) were masked by the time by treatment interaction. DON concentrations also fluctuated greatly throughout 2002 (time, time by treatment interaction; $p \leqslant 0.0001$) and 2003 (time, $p \leqslant 0.0001$, time by type interaction, $p = 0.0002$). Differences of dissolved organic N among urban landscapes were also not detected due to the time by treatment interaction and weak type effects ($p > 0.074-0.501$). Seasonal mean data for both MIN and DON was not appropriate for detecting urban landscape differences because the time by treatment interactions were not orderly (Table 3).

The accuracy of the LOI method was verified with linear regression of fPOM carbon contents determined by automated dry combustion and g fPOM m^{-2} determined by LOI ($R^2 = 0.90$). Linear regression was also performed with values of total SOM determined by LOI and Walkley–Black methods (Midwest Laboratories, Omaha, NE), on 04/17/02, 10/03/02, 04/11/03, and 10/10/03 ($R^2 = 0.69$, 0.77, 0.86, and 0.89).

In 2002, litter SOM, coarse POM, and fine POM did not significantly change within the growing season ($p > 0.14$), but a significant time effect was detected for total SOM and mineral-associated SOM ($p \leqslant 0.0001$). In 2003, a significant time effect was detected for all SOM fractions ($p \leqslant 0.030$) (Table 4). Total SOM, litter SOM, cPOM, fPOM, and mineral-associated SOM main treatment effects were significant on most dates (16 of 16, 12 of 16, 15 of 16, 15 of 16, and 16 of 16, respectively). Although significant, the time by treatment interactions in both 2002 and 2003 were orderly. The contributions of litter SOM, coarse POM, fine POM, and mineral-associated SOM to total SOM varied among the urban landscapes but changes in these relative contributions did not occur with time. Mineral-associated SOM (53–84%) made up the largest portion of tSOM, and lSOM (1–10%) the smallest on all urban landscapes. Fine POM (7–22%) was the second largest contributor to tSOM, and cPOM (5–14%) the third largest portion on old residential, park, street, and old mulch sites. Coarse POM (8–25%) was the second largest contributor to tSOM followed by fPOM (7–15%) on new mulch and new residential sites.

Table 4. Soil organic matter mean values from six urban landscapes in Moscow, ID and Pullman, WA in 2002 and 2003

	$kg\,m^{-2}$					TOC ($mg\,g^{-1}$)	C/N	
	tSOM	maSOM	fPOM	cPOM	lSOM		fPOM	cPOM
2002								
NML	12.423 ab	7.458 b	1.379 bc	2.606 a	0.980 a	23.6 ab	15.5 a	27.7 a
NRL	8.574 c	6.277 b	0.941 c	1.000 b	0.356 b	14.9 c	17.9 a	28.1 a
OML	10.448 bc	8.229 a	0.980 c	0.853 b	0.386 b	20.0 bc	20.5 a	34.5 a
ORL	13.739 a	10.259 a	2.033 a	1.053 b	0.394 b	29.3 a	16.3 a	25.1 a
PAL	14.307 a	10.955 a	1.978 a	0.985 b	0.389 b	30.3 a	15.7 a	26.1 a
STL	12.027 ab	8.320 a	1.741 ab	1.319 b	0.647 ab	26.6 ab	20.5 a	26.9 a
2003								
NML	13.529 ab	9.055 b	1.220 bc	2.216 a	1.038 a	23.8 ab	15.9 a	26.7 a
NRL	10.599 c	7.927 b	1.047 c	1.197 b	0.428 b	16.2 c	19.8 a	30.5 a
OML	11.787 bc	9.501 a	1.018 c	0.886 b	0.382 b	20.7 bc	20.4 a	35.0 a
ORL	15.740 a	12.301 a	1.900 a	1.073 b	0.466 b	30.6 a	16.6 a	25.2 a
PAL	15.942 a	12.828 a	1.777 a	0.913 b	0.424 b	31.0 a	16.1 a	25.7 a
STL	13.830 ab	10.608 a	1.492 ab	1.173 b	0.557 ab	27.1 ab	20.5 a	28.9 a

Means with same letter are not significantly different at $p \leqslant 0.05$.

Total SOM was significantly greater on old residential ($14.7\,kg\,m^{-2}$) and park sites ($15.1\,g\,m^{-2}$), followed by street ($13.0\,kg\,m^{-2}$), new mulch ($13.0\,kg\,m^{-2}$), old mulch ($11.1\,kg\,m^{-2}$), and new residential sites ($9.6\,kg\,m^{-2}$) (Table 4). Litter SOM and coarse POM were significantly greater on new mulch sites (1.0 and $2.4\,kg\,m^{-2}$) compared to all other urban landscapes (0.44 and $1.0\,kg\,m^{-2}$). Fine POM was significantly greater on old residential ($2.0\,kg\,m^{-2}$) and park ($1.9\,kg\,m^{-2}$), followed by street ($1.6\,kg\,m^{-2}$), new mulch ($1.3\,kg\,m^{-2}$), old mulch ($1.0\,kg\,m^{-2}$), and new residential sites ($1.0\,kg\,m^{-2}$). Mineral-associated SOM was significantly greater on old residential ($11.3\,kg\,m^{-2}$) and park sites ($11.9\,kg\,m^{-2}$) and lowest on new residential sites ($7.1\,kg\,m^{-2}$). Mineral-associated SOM on street sites ($9.5\,kg\,m^{-2}$) was significantly greater than old mulch ($8.9\,kg\,m^{-2}$) and new mulch sites ($8.3\,kg\,m^{-2}$).

The time and time by treatment interactions for POM C/N ratios were significant in 2002 and 2003 ($p \leqslant 0.007$). Consistent differences for POM C/N ratios were observed and interactions were orderly. The C/N ratios of the fPOM fraction were greater on new residential, old mulch, and street sites (20/1) compared to old residential, park, and new mulch sites (16/1) (Table 4). The cPOM C/N ratios were greater on old mulch (35/1) compared to other urban landscapes (27/1). The C/N ratios of fine POM fractions (16/1–21/1) were less than the C/N ratios of the coarse POM fractions (24/1–36/1).

Discussion

Soil development occurs through interactions of climate, organisms, relief, parent material, and time (Jenny, 1941). Of the developmental factors, time played the most significant role in physical, chemical, and biological differences among these urban soils. Old residential, street, and park sites had substantially longer times since initial disturbances (mean of 64 years old). Conversely, new residential, old mulch, and new mulch landscapes were all less than 20 years old (mean of 9 years old). We believe that as time since initial disturbance increases, the associated impacts of urbanization are reduced by synergistic processes improving physical, biological, and chemical soil properties. Specifically, reductions in bulk density, increases in microbial biomass and activity, and increases in organic matter occur as urban soils develop.

Compared to new residential soils, old residential soils had decreased bulk densities (19%) (Table 2). In general, sandy soils have less aggregation and higher bulk densities (Brady and Weil, 2002), but we found new urban soils with higher bulk densities and higher clay contents (43%). We attribute this anomaly to reduced biological activity and organic matter, and more recent compaction from building site preparation on newer urban landscapes. Soil microorganisms promote aggregation, thus reduce soil bulk density (Rice et al., 1996). Organic matter is highly porous and has a particle density of

1.2–1.5 g cm^{-3}; therefore, when incorporated in the soil, decreases soil bulk density (Sylvia et al., 1999). Soil compaction increases bulk density by reducing total pore volume and increasing the percentage of small pores. Clay translocation is indicative of soil development (Birkeland, 1999). We did not measure clay contents below 15 cm, but it is likely that new and old residential sites had similar initial clay contents. Because clay contents in the top 15 cm were greater on newer urban sites, we believe less eluviation has occurred in these profiles compared to older urban landscapes. Relative decreases of clay in the upper profile and decreases of bulk densities in older urban landscapes suggest these soils are further developed than those on newer urban sites.

Soil organic matter from old residential sites was significantly greater than on new residential landscapes, total SOM (35% greater), mineral-associated SOM (37% greater), and fine POM (50% greater) (Table 4). As soils develop, organic matter accumulates (Birkeland, 1999). Boerner et al. (1998) found that organic carbon contents increased with greater time since disturbance. Our results also show that as time since disturbance increases soil organic matter contents are increased. In addition, the C/N ratios of the coarse and fine POM fractions from new residential sites were 14% and 13% higher than old residential landscapes (Table 4). Residues with higher C/N ratios promote activity of general purpose decay organism over nitrifying organisms (Brady and Weil, 2002). A nitrification depression period persists until activities of decay organisms subside from a lack of easily oxidizable carbon; and, nitrification proceeds following drop offs in microbial numbers, carbon dioxide formation, and nitrogen demand. Potential nitrogen immobilization and higher C/N ratios were measured on new and not old residential sites. Fine POM had lower C/N ratios and smaller particle sizes compared to coarse POM. The relative contributions of fine to coarse POM were greater in older compared to newer urban landscapes. Decreased C/N ratios and increased fine to coarse POM ratios are evidence of increased soil development in older urban sites. Beyer et al. (1995) also studied temporal changes in urban soil organic matter and found younger soils (10–20 years old) dominated by free litter compounds, and older soils (greater than 100 years old) with more SOM incorporated into the humic matrix. Both Beyer et al. (1995) and our results show that temporal changes in urban soil organic matter are detectable within a century.

Compared to new residential landscapes, old residential landscapes had increased microbial biomass and activity, microbial biomass N (71%), potential C mineralization (20%), potential N mineralization (83%) (Table 3). We propose that high bulk densities and low soil organic matter on newer urban sites contributed to low microbial biomass and activities on these sites. Breland and Hansen (1996) found that compaction reduced nitrogen mineralization by increased physical protection of organic materials from microbial attack. Reductions in soil bulk density and organic matter accumulations have been linked to enhanced soil biological processes and nitrogen cycling. For instance, soil decompaction in conservation lands was found to improve recovery efficiency of croplands by increasing the rate of response of amino sugar concentrations (Amelung et al., 2001).

Beyer et al. (1995) found higher C_{mic}/TOC and qCO_2 values for younger urban soils to be indicative of early soil development. Similarly, we found qCO_2 values decreased exponentially with increasing landscape age. The decreasing qCO_2 values suggest that the impact of site disturbance decreases rapidly with time and older urban landscapes are closer to steady-state conditions relative to younger urban landscapes. Our C_{mic}/TOC ratios on older urban landscapes (10–15) were near values of similar aged soils (Insam and Domsch, 1988; Beyer et al., 1995). Unlike, Beyer et al. (1995), we found lower C_{mic}/TOC ratios on younger urban soils. We believe that C_{mic}/TOC ratios are low on the newer urban sites because of abnormally low microbial biomass and extraneous carbon inputs (mulch and grass clippings), resulting in C_{mic}/TOC ratios below values observed in other environmental systems. MBC on newer urban sites ranged from 82 to 132 $\mu g\, g^{-1}$, compared to other studies with ranges of 200 to 2859 $\mu g\, g^{-1}$ (Insam and Domsch, 1988; Insam et al., 1989; Beyer et al., 1995). Lower C_{mic}/TOC ratios indicate later successional stages (Insam and Domsch, 1988), but we suspect that soils on newer urban landscapes have yet to build up significant microbial populations relative to amounts of organic carbon.

Studies of soil development in urban soils are scarce, but research in other systems have suggested similar succession patterns to what we found in these urban soils (Zak et al., 1990; Diquelou et al., 1999). In studies of old field successions in Brittany, France, Diquelou et al. (1999) found that in the first decades after agriculture, organic matter, nitrogen, and microbial activity tended to decline. Increases in organic matter, nitrogen, and microbial activity then occurred with forest species establishment (Diquelou et al., 1999). Zak et al. (1990) associated top soil differentiation with increased in organic

matter, nutrients, and microbial biomass. After abandonment, organic matter inputs are restored, and the termination of soil disturbances allow organic matter and nitrogen mineralization increases (Pastor et al., 1987; Zak et al., 1990). Similar successional steps are recognized in these urban soils. In urban soils less than 10 years we observed increased bulk densities, reduced microbial biomass and activity, and reductions in soil organic matter. We distinguished soil developmental processes on older compared to newer urban sites by decreased bulk densities, increased microbial biomass and activity, and increased quantity and quality of soil organic matter.

Conclusion

Urban soils are distinguishable within urban environments. Physical, chemical, and biological properties are modified by a significant site disturbance for urban infrastructure. Time is an important soil developmental factor for distinguishing soils in urban environments. Urban landscapes with increased time since initial disturbance have been found with reduced soil bulk densities, increased biological activity, and increased soil organic matter. Future research should examine urban soil properties in various spatial and temporal scales. This would allow urban soil developmental processes to be described in more detail and provide more specific information about the spatial and temporal variability in urban soils.

Acknowledgments

The authors thank Richard Gill, Ph.D., Donald Thill, Ph.D., Robert Tripepi, Ph.D., and the anonymous reviewers for their suggestions. We also thank the ISA Research Trust (John Duling Grant) and the University of Idaho Seed Grant for their support of this project.

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