Particle Density of Aspen, Spruce, and Pine Forest Floors in Alberta, Canada

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ABSTRACT

Soil particle density (ρ_s), the ratio of the mass of soil solids to the volume of solids, is used to derive such properties as soil porosity and heat capacity, which are critical to understanding and modeling water, energy, and nutrient fluxes through forested landscapes. Values of forest floor ρ_s and organic matter particle density (ρ_o) vary widely in the literature, so it is difficult to know which values are appropriate under different circumstances. We measured ρ_s, ρ_o, bulk density (ρ_b), loss-on-ignition (LOI), and total C for a range of forest types in northern Alberta, Canada. Although samples were obtained from a diverse range of forest types, our measured values of forest floor ρ_s (1.52–1.60 Mg m^{-3}) and calculated values of ρ_o (1.41–1.44 Mg m^{-3}) showed no statistically significant differences among stand types. The measured values of ρ_s and ρ_o were greater than many values in the literature, potentially due to differences in measurement methods. Measurements of ρ_s should be performed across a range of forest floor and organic soil types to refine our understanding of the variation in this fundamental soil property.

The ρ_s is the ratio of the mass of soil solids to the volume of those same solids, which differs from the ρ_b of a soil, which is the ratio of the mass of soil solids to the bulk soil volume (solids + pores). Particle density is required to derive such soil properties as porosity, relative saturation, heat capacity, and thermal conductivity. Therefore, the accurate measurement of ρ_s is critical for such applications as modeling water and energy transport processes in soils (Ogee and Brunet, 2002) or calibrating soil moisture sensors (Schaap et al., 1996).

In forested ecosystems, soil surface organic horizons (i.e., forest floors) influence many important hydrological and biogeochemical processes by mediating energy and water fluxes between the atmosphere and the mineral soil rooting zone (Schaap and Bouten, 1997; Kelliher et al., 2001; Ogee and Brunet, 2002). Forest floors are mostly composed of organic materials, including plant detritus, such as leaf litter and woody materials, microbial tissues, and products of decomposition. Thus, the particle density of a forest floor is a function of the particle density of these organic materials (ρ_o) along with the particle density of any mineral material (mineral particle density, ρ_m) incorporated into the organic tissues or mixed into the forest floor. While ρ_m is generally assumed to be 2.65 Mg m^{-3} for quartz-dominated mineral materials (Brady and Weil, 1990; Skopp, 2000; Jury and Horton, 2004), values of ρ_o vary widely in the literature (Table 1) and measurement methods are not provided in most reference books and texts.

Few published studies have reported measured values of forest floor ρ_s, and the results are highly variable (0.47–1.38 Mg m^{-3}; Table 1). In addition to direct measurements, forest floor ρ_s can be estimated using assumed values of ρ_o and ρ_m, and measured values of organic matter content (Adams, 1973). Using assumed ρ_o and ρ_m values of 1.5 and 2.65 Mg m^{-3}, respectively, Lauren and Heiskanen (1997) estimated the forest floor ρ_s of a Scots pine stand in Finland to be 1.65 Mg m^{-3}, while Lauren and Mannerkoski (2001) estimated the forest floor ρ_s of Finnish Norway spruce and Scots pine stands to be 1.57 and 1.61 Mg m^{-3}, respectively. Neither forest floor ρ_s or ρ_o values are provided in two popular texts on forest soils (Armson, 1977; Fisher and Binkley, 2000), both of which discuss the importance of the forest floor at great length.

A sound knowledge of forest floor physical properties is essential on the boreal plain of northern Canada because the subhumid climate is dominated by precipitation that is less than potential evapotranspiration in most years (Devito et al., 2005). As a result, water and nutrient movement through the forest floor is highly dependent on moisture conditions (Wolniewicz, 2002; Whitson, 2003). In addition, the forest floor is the dominant rooting zone for many boreal tree species (Strong and LaRoi, 1983), so the water relations of the forest floor are critical in understanding both forest productivity and landscape-scale hydrological patterns. Given the wide range of ρ_o and forest floor ρ_s values in the literature, it is difficult to know which value to employ for research areas on the boreal plain of northern Alberta, Canada. The objectives of this research were to determine the ρ_s and ρ_o values of a range of forest floor types, with an aim to reducing the uncertainty in selecting appropriate values of ρ_s and ρ_o. We selected forest floor samples from three stand types at two sites on the boreal plain of northern Alberta.

MATERIALS AND METHODS

Samples were collected as part of the Hydrology Ecology and Disturbance (HEAD) project at the Utikuma Research Study Area (URSA) near Utikuma Lake (56°20′ N, 115°30′ W) and the Ecosystem Management Emulating Natural Disturbance (EMEND) experimental site located north of the town of Peace River (56°46′ N, 118°22′ W), approximately 200 km west of URSA. Both sites are situated in the Boreal Plains Ecozone (EcoRegions Working Group, 1989) and have cold winters and warm summers. Average annual precipitation and

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Abbreviations: ρ_b, bulk density; ρ_o, organic matter particle density; ρ_m, mineral particle density; ρ_s, soil particle density; EMEND, Ecosystem Management Emulating Natural Disturbance; HEAD, Hydrology, Ecology and Disturbance; LOI, loss-on-ignition; URSA, Utikuma Research Study Area.

Table 1. Published particle density values for organic matter (ρ_o), forest floor (FF), and wood (ρ_s). Material type descriptions are taken from original sources.

Material type	ρ_o	ρ_s	Method	Source
	Mg m^{-3}	Mg m^{-3}		
Organic matter	1.3		Estimated†	Adams (1973)
Organic matter	1.55		Not given	Verdonck et al. (1978)
Organic matter	1.1–1.4		Not given	Brady and Weil (1990)
Organic matter	1.51–1.52		Estimated‡	Heiskanen (1992)
Organic matter	1.0		Not given	Skopp (2000)
Organic matter	1.3		Not given	Jury and Horton (2004)
Organic matter	1.3		Not given	de Vries (1963)
Humus-forest		1.26		
Humus	<1.5		Not given	Blake and Hartge (1986)
Humus-douglas fir		0.6	Not given	Fosberg (1977)
Humus-ponderosa pine		0.47		
Humus-lodgepole pine		0.56		
Duff-douglas fir		0.6		
Duff-ponderosa pine		0.51		
Duff-lodegepole pine		0.56		
FF-scots pine		1.65	Estimated§	Lauren and Heiskanen (1997)
FF-pine needles		1.38	Measured, gas pycnometer	van Donk and Tollner (2000)
FF-norway spruce		1.57	Estimated§	Lauren and Mannerkoski (2001)
FF-scots pine		1.61		
FF-maritime pine		0.82	Measured¶	Ogee and Brunet (2002)
Wood-cell wall material		1.46–1.53	Measured, liquid and gas pycnometers	Siau (1995)
Wood-cell wall material		1.5	Not given	Haygreen and Bowyer (1996)
Wood-pine		0.35–0.85	Not given	Lide (2002)
Wood-spruce		0.48–0.7		
Wood-poplar		0.35–0.5		

† Estimated from measured ρ_s and loss on ignition (LOI) values of forest soils and assuming ρ_m of 2.65 Mg m^{-3}.
‡ Estimated from measured ρ_s and LOI values of peat and assuming ρ_m of 2.65 Mg m^{-3}.
§ Estimated from measured ρ_b and LOI and assuming ρ_o of 1.5 Mg m^{-3} and ρ_m of 2.65 Mg m^{-3}.
¶ Measured using a hydraulic press to compact known mass of dry forest floor and measuring compacted volume.

potential evapotranspiration for the region around URSA are 469 and 517 mm, respectively, while the same variables for EMEND are 431 and 504 mm, respectively (Agriculture and AgriFood Canada, 1997). The soils at URSA are developed on outwash, glacial till, and lacustrine deposits, with a total elevation range from 640 to 680 m above sea level (asl) across the 50-km wide study area. The elevation ranges from 677 to 880 m asl at EMEND, and the landscape is rolling till and low-lying lacustrine deposits. The soils at both sites are typically haplocryalfs on fine-textured till and lacustrine deposits and cryoboralfs on coarse textured outwash deposits (Soil Survey Staff, 1998).

Harvesting of the clearcuts at EMEND was completed in the winter of 1998–1999, 3.5 yr before sample collection. Whole trees were harvested using a feller-buncher and skidded directly to the landing, where stems were delimbed. Debris from the delimbing process was piled on the landing and burned (Sidders and Luchkow, 1998).

Forest floor samples were collected slightly differently at URSA and EMEND because they were originally used for separate studies. At URSA, random samples were selected within three replicates each of undisturbed stands dominated by trembling aspen (*Populus tremuloides* Michx.), by white spruce [*Picea glauca*, (Moench) Voss] or by jack pine (*Pinus banksiana* Lamb) (nine experimental units in total). At each sampling site, the forest floor was collected by removing all of the forest floor material (i.e., Oi + Oe + Oa horizons [Soil Survey Staff, 1998] or L + F + H horizons [Green et al., 1993]) within a 0.15 m by 0.15 m surface area to the depth of the mineral soil surface. The thickness of the forest floor (from the upper surface of the Oi horizon to the surface of the mineral soil) was measured along the sides of the 0.15 m × 0.15 m cavity. At EMEND, random samples were selected within three replicates each of undisturbed and clearcut stands dominated by trembling aspen or by white spruce (12 experimental units in total). At each sampling site, the forest floor was collected by removing the Oe and Oa horizons of the forest floor within a 0.15 m by 0.15 m surface area to the depth of the mineral soil surface (i.e., the Oi horizon was excluded at EMEND). The thickness of the forest floor (from the upper surface of the Oe horizon to the surface of the mineral soil) was measured along the sides of the 0.15 m × 0.15 m cavity. At both study sites, humus forms were classified according to the system of Green et al. (1993).

To determine the dry mass for ρ_b (Mg m^{-3}), forest floor samples were dried at 70°C for 48 h. After oven-drying, aliquots of each forest floor sample were ground to pass a 2-mm sieve. Organic matter LOI (g kg^{-1}) was measured by heating a portion of the ground samples at 375°C for 1 h, followed by 6 h at 500°C (Ball, 1964). Total C concentrations (g kg^{-1}) of forest floor samples were determined by combustion on a Costech C/N Elemental Analyzer. Forest floor ρ_s (Mg m^{-3}) was measured using the liquid pycnometer method, with de-aired water as the displacing liquid (Blake and Hartge, 1986). After wetting with de-aired water, ground forest floor samples were boiled in a hot water bath (Heiskanen, 1992) until they had been completely degassed. The mean measured ρ_s value for quartz sand samples (used as a positive control) was 2.65 Mg m^{-3} (standard deviation 0.012). This value is the same as the ρ_m of 2.65 Mg m^{-3} found in the literature, confirming the accuracy of the liquid pycnometer method for mineral matter. Values obtained using this method are the ρ_s of the whole forest floor (organic + mineral fractions). The particle density of the organic fraction (ρ_o, Mg m^{-3}) was calculated according to Adams (1973):

$$\rho_o = \frac{(\mathrm{LOI} \times \rho_s)}{\left[100 - \rho_s \times \dfrac{(100 - \mathrm{LOI})}{\rho_m}\right]} \quad [1]$$

where LOI is expressed as percentage of mass loss.

Forest floor ρ_b, thickness, LOI, total C, ρ_s, and ρ_o were analyzed using one-way analysis of variance (ANOVA) to determine the effects of stand type (URSA or EMEND) or disturbance history (EMEND only) within study sites using SAS (version 8.01, SAS Institute Inc. 1999-2000, Cary, NC). Forest

Table 2. Forest floor bulk density (ρ_b), thickness, loss-on-ignition (LOI), and total C content for stand types at URSA and EMEND. Values are means with standard deviation in parentheses ($n = 3$). Forest floor types follow Green et al. (1993).

Site	Stand type	Disturbance history	Forest floor type	Horizons included	ρ_b	Thickness	LOI	Total C
					Mg m^{-3}	m	g kg^{-1}	
URSA	Aspen	Forest	Mormoder	Oi + Oe + Oa	0.075 (0.019)	0.099 (0.018)a†	832.6 (91.4)	475.5 (21.9)
URSA	Spruce	Forest	Hemimor	Oi + Oe + Oa	0.104 (0.029)	0.073 (0.033)ab	783.7 (27.4)	422.8 (18.0)
URSA	Pine	Forest	Hemimor	Oi + Oe + Oa	0.084 (0.029)	0.032 (0.003)b	792.6 (69.3)	436.0 (42.7)
EMEND	Aspen	Forest	Mormoder	Oe + Oa	0.080 (0.008)y‡	0.063 (0.004)ay	816.1 (5.5)y	428.1 (17.7)y
EMEND	Aspen	Clearcut	Mormoder	Oe + Oa	0.094 (0.012)	0.085 (0.016)b	812.4 (53.5)	442.3 (28.4)
EMEND	Spruce	Forest	Humimor	Oe + Oa	0.059 (0.010)z	0.13 (0.023)z	877.5 (24.3)z	468.1 (9.0)z
EMEND	Spruce	Clearcut	Humimor	Oe + Oa	0.068 (0.017)	0.098 (0.012)	855.9 (14.7)	467.5 (12.2)

† At URSA, the letters a and b refer to statistically significant differences ($P < 0.05$) between stand types.

‡ At EMEND, the letters a and b refer to statistically significant differences ($P < 0.05$) between forest and clearcut within a stand type; the letters y and z refer to statistically significant differences ($P < 0.05$) between stand types for a given treatment. Where there were no statistically significant differences between stand types, no letters are given.

floors from the two study sites (URSA vs. EMEND) were not compared because samples from URSA and EMEND included different forest floor horizons.

RESULTS AND DISCUSSION

Forest floor samples from the URSA and EMEND experimental sites were selected for this study because they represent a variety of stand types, parent materials, disturbance histories, and humus forms (Table 2) and were, therefore, expected to possess different physical and chemical characteristics. As such, the thickness of the Oi + Oe + Oa layer was significantly greater in aspen stands than in jack pine stands at URSA (Table 2; $P = 0.024$). At EMEND, the bulk density of the Oe + Oa layer was significantly greater in unharvested aspen stands than in unharvested spruce stands ($P = 0.047$), while forest floor thickness, LOI and total C were significantly greater in unharvested spruce stands than in unharvested aspen stands ($P = 0.009$, $P = 0.013$, and $P = 0.025$, respectively). Within aspen stands at EMEND, the depth of the Oe + Oa layer was significantly greater in clearcuts than in unharvested forests ($P = 0.036$). A previous study of the forest floor at EMEND also found differences in the chemical composition of aspen and spruce forest floors. Specifically, forest floors from unharvested aspen stands were richer in carbonyl C (i.e., oxidized forms of C, such as ketones and carboxyl groups) while forest floors in unharvested spruce stands were richer in aromatic C, in particular from condensed tannins (Hannam et al., 2004).

Despite the strong differences in other forest floor properties, measured values of ρ_s and calculated values of ρ_o did not vary significantly between stand types or disturbance histories at either study site (Table 3). The mean ρ_s ranged from a minimum of 1.52 Mg m^{-3} for spruce forest floor at EMEND to a maximum value of 1.60 Mg m^{-3} for spruce forest floor at URSA, with all other values occurring within this range (Table 3). The calculated mean ρ_o values ranged from 1.41 Mg m^{-3} for jack pine forest floors up to 1.44 Mg m^{-3} for spruce forest floors, both at URSA (Table 3). Although the two sites were not compared statistically, there was a relatively large difference between the ρ_s of spruce forest floor at URSA (1.60 Mg m^{-3}) and at EMEND (1.52 Mg m^{-3}). Given that LOI was greater for the spruce forest floors at EMEND than at URSA, while ρ_o values of the spruce forest floors at the two sites were very similar, the lower values of ρ_s for spruce forest floor at EMEND are probably the result of greater organic matter content. Differences in organic matter content between URSA and EMEND may be due to differences in forest floor morphology and composition. Spruce forest floors at EMEND were humimors and were dominated by decomposing moss tissue. At URSA, spruce forest floors were hemimors and were dominated by decomposing spruce foliage and woody (twigs and cones) material.

The values of ρ_s obtained from forest floor samples in this study are higher than many previously published values (Table 1). Such discrepancies may be the result of differences in measurement methods. The methods used by de Vries (1963) and Fosberg (1977) were not provided. However, Ogee and Brunet (2002) used a mechanical press to compact a known mass of dry forest floor and then measured its compacted volume (Y. Brunet, INRA France, 2002 personal communication). This method is likely to underestimate the forest floor ρ_s because of incomplete evacuation of air within intercellular pores. van Donk and Tollner (2000) used a gas pycnometer system to measure forest floor particle densities. Although we know of no studies that have compared the results of gas and liquid methods, Heiskanen (1992) concluded that the use of water as the displacing agent is the most accurate liquid displacement method.

The calculated values of ρ_o from the current study (mean 1.43 Mg m^{-3}) are within the high end of the range of published values (Table 1). Sources that determined ρ_o in the same manner as we did reported values of 1.3 Mg m^{-3} for forest soil surface organic horizons in Wales (Adams, 1973), 1.5 Mg m^{-3} for horticultural peat (Heis-

Table 3. Measured forest floor particle density (ρ_s, Mg m^{-3}) and calculated organic matter density (ρ_o, Mg m^{-3}) values. Values are means with standard deviation in parentheses ($n = 3$). For the URSA sites, there were no significant differences ($P < 0.05$) in ρ_s and ρ_o between stand types. For EMEND sites, there were no significant differences ($P < 0.05$) between stand types within treatment types, or between treatment types for any stand type.

Site	Stand type	Disturbance history	ρ_s	ρ_o
			Mg m^{-3}	Mg m^{-3}
URSA	Aspen	Forest	1.54 (0.021)	1.42 (0.056)
URSA	Spruce	Forest	1.60 (0.018)	1.44 (0.006)
URSA	Pine	Forest	1.56 (0.065)	1.41 (0.009)
EMEND	Aspen	Forest	1.57 (0.018)	1.43 (0.024)
		Clearcut	1.57 (0.053)	1.43 (0.012)
EMEND	Spruce	Forest	1.52 (0.032)	1.43 (0.016)
		Clearcut	1.53 (0.008)	1.42 (0.005)

kanen, 1992), and 1.40 to 1.47 Mg m^{-3} for a range of organic wetland soils (T.E. Redding and K.J. Devito, Univ. of Alberta, unpublished data, 2002). It is interesting that a very small range of ρ_o (1.3–1.5 Mg m^{-3}) values have been obtained in the current study and from other published studies that used the same measurement method, despite the wide range of organic materials examined. It is also important to consider that calculated ρ_o values are dependent on the value of ρ_m used. While a ρ_m of 2.65 Mg m^{-3} is standard, variation in the mineral composition of the soil (Brady and Weil, 1990; Skopp, 2000) could introduce error into the calculation of ρ_o.

CONCLUSIONS

The results of this study have shown that the ρ_s and ρ_o of forest floors do not vary significantly across stand types or humus forms common to the boreal plain of northern Alberta. This was surprising, given the significant differences observed in other forest floor properties, and the range of climatic conditions and parent materials represented. However, the ρ_s of these forest floors are greater than many of the values of ρ_s presented in the literature. In the future, we suggest that forest floor ρ_s should either be estimated after determination of forest floor LOI, using an assumed ρ_o value for the stand type of interest (Table 3) or our mean calculated value of 1.43 Mg m^{-3} (within the literature range for measured values of 1.3–1.5 Mg m^{-3}), or be measured directly using the liquid pycnometer method. We recommend that the results of this study be used for sites on the boreal plain, to improve the estimation and modeling of forest hydrological and soil biogeochemical processes that involve the forest floor (e.g., Wolniewicz, 2002). Further measurements of ρ_s and a comparison of measurement methods for estimating ρ_s should be performed across a wider range of ecosystems and forest floor and organic soil types to reduce our reliance on unreferenced standard values presented in textbooks and reference materials.

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