

The organic fraction – bulk density relationship and the expression of nutrient content in forest soils

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Bulk density of forest soils from nine locations in New England was closely and inversely related to the organic fraction of the soil. Measured data over the whole range of organic fractions followed the theoretical relationship $D_b = D_{bm}D_{bo} / [F_o D_{bm} + (1 - F_o)D_{bo}]$ where D_b is the bulk density (Mg/m^3), F_o is the organic fraction (kg_o/kg), D_{bo} is the bulk density when $F_o = 1$, and D_{bm} is the bulk density when $F_o = 0$. The relation arises from assuming that (i) D_{bo} , the bulk density of "pure" organic matter, and D_{bm} , the bulk density of "pure" mineral matter, are constant and (ii) in a mixture, the volumes occupied by the organic mass and the mineral mass are additive. For forest soils on coarse-textured till in New England, $D_{bo} = 0.11 Mg/m^3$ and D_{bm} varied from 1.45 Mg/m^3 for sandy loams to 2.19 Mg/m^3 for silt loams. When these parameters are known, D_b can be estimated from F_o , which is more easily measured. When F_o is greater than 0.1 kg_o/kg , the organic mass per unit soil volume ($F_o D_b$), or organic density, is approximately constant at 0.1 Mg_o/m^3 . For many nutrients, separate evaluation of the organic density and the amount of nutrient per unit organic mass may facilitate intersite comparisons for studies of nutrient availability and leaching.

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La densité apparente de sols forestiers de neuf stations en Nouvelle-Angleterre était étroitement et inversement reliée à la fraction organique du sol. Les données mesurées sur des sols avec des teneurs en matière organique très variables ont suivi la relation théorique $D_b = D_{bm}D_{bo} / [F_o D_{bm} + (1 - F_o)D_{bo}]$ où D_b est la densité apparente (Mg/m^3), F_o est la fraction organique (kg_o/kg), et les deux paramètres sont D_{bo} , la densité apparente quand $F_o = 1$, et D_{bm} , la densité apparente quand $F_o = 0$. La relation est obtenue en assumant que (i) D_{bo} , la densité apparente d'une matière organique "pure", et D_{bm} , la densité apparente d'une matière minérale "pure", sont constantes et (ii) en mélange, les volumes occupés par la masse organique et la masse minérale sont additifs. Pour les sols forestiers sur un till de texture grossière en Nouvelle-Angleterre, $D_{bo} = 0,11 Mg/m^3$ et D_{bm} a varié de 1,45 Mg/m^3 pour les sables loameux à 2,19 Mg/m^3 pour les loams limoneux. Quand ces paramètres sont connus, D_b peut être estimé à partir de F_o , lequel est plus facilement mesuré. Quand F_o est supérieur à 0,1 kg_o/kg , la masse organique par unité de volume de sol ($F_o D_b$), ou la densité organique, est relativement constante à 0,1 Mg_o/m^3 . Pour plusieurs nutriments, l'évaluation séparée de la densité organique et de la quantité de nutriments par unité de masse organique peut faciliter les comparaisons entre les stations pour des études sur la disponibilité et le lessivage des nutriments.

[Traduit par la rédaction]

Introduction

Organic matter content and bulk density are related soil properties that are important to nutrient studies in northeastern forests. Many nutrients are closely tied to organic matter and its decomposition. Values of bulk density are necessary to convert laboratory measurements of soil nutrient concentrations, exchange capacities, water contents, and biological populations from a mass basis to a volume or area basis.

Unfortunately, bulk density, D_b , can be difficult to measure both in low-density and root-filled organic (O) horizons and in stony mineral horizons of forest soils. But D_b is closely related to organic mass fraction, F_o , which can be easily determined by loss on ignition in acidic forest soils (Ball 1964). D_b tends to decrease as F_o (organic mass per unit soil mass) increases, particularly in forest soils, which tend to be high in organic matter and in aggregate stability near the surface.

Gorham (1953) showed that D_b increased as F_o decreased in forest O horizons. Curtis and Post (1964) developed an empirical regression of $\log D_b$ on $\log F_o$ (loss on ignition); this equation was valid for O, A, E, and B horizons of Vermont forest soils. Federer (1983) and Huntington et al. (1989) obtained very similar equations for forest soils of central New Hampshire. Jeffrey (1970) suggested that the relationship between organic matter and D_b might be universal.

In this paper we develop an apparently new theoretical expression for the relationship between F_o and D_b . The expression is tested both on our own data from forest soils in New England and on the data of Curtis and Post (1964) and Jeffrey (1970). Variation in D_b is shown to be largely a consequence of variation in F_o . Organic density, or organic mass per unit soil volume, $F_o D_b$, is found to be rather constant when $F_o > 0.1$, as in the nutrient-rich surface horizons of forest soils. Organic density is discussed as a useful concept for the comparison of results in nutrient studies.

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TABLE 1. Location code, state, cover type, stand age, number of samples, and citation describing the study area

Code	State	Cover	Stand age (years)	No. of samples	Site descriptions
C1	Conn.	CHD	80	41	Tritton et al. 1987
M1	Me.	SF	65	27	Smith et al. 1986
M2	Me.	SF	2	132	Turcotte et al. 1991
N1	N.H.	NHD	1	32	
N2	N.H.	NHD	3	28	Melillo et al. 1983
N3	N.H.	NHD	30	20	Melillo et al. 1983
N4	N.H.	NHD	50+	28	Melillo et al. 1983
N5	N.H.	NHD	70	40	Huntington et al. 1989
N6	N.H.	NHD	12, 40, 44, 80+	132	Federer 1982

Note: CHD, central hardwood; SF, spruce-fir; NHD, northern hardwood.

Theory

A mass of "pure" mineral soil material (with no organic matter), m_m , occupies a volume, V_m , and therefore has a bulk density, D_{bm} , defined as m_m/V_m . Similarly, a mass of "pure" organic soil (with no mineral matter), m_o , occupies a volume, V_o , and has a bulk density, D_{bo} , defined as m_o/V_o . The F_o of some mixture of such mineral and organic masses is defined as

$$[1] \quad F_o = \frac{m_o}{(m_o + m_m)}$$

The mixture has a volume, V , and its D_b is $(m_o + m_m)/V$. We make the theoretical assumptions that (i) D_{bm} and D_{bo} remain constant in any mixture and (ii) the volume occupied by the organic fraction and the volume occupied by the mineral fraction in the mixture are additive, just as the masses are, so

$$[2] \quad V = V_m + V_o$$

Substituting the definitions of D_b , D_{bm} , D_{bo} , and F_o into eq. 2 leads to the theoretical equation

$$[3] \quad D_b = \frac{D_{bm}D_{bo}}{F_o D_{bm} + (1 - F_o)D_{bo}}$$

In a graph of D_b versus F_o , D_{bm} and D_{bo} are the D_b values at the end points $F_o = 0$ and $F_o = 1$, respectively. These two end points completely define the theoretical curve; its nonlinear shape derives from the underlying assumptions, not from the parameter values.

Methods

Study locations

In this paper, we test the theoretical eq. 3 against field data obtained by us between 1979 and 1986 as a component of several studies of nutrient responses to whole-tree harvesting. Samples were collected from nine locations in three states and three cover types (Table 1). Location descriptions are given in detail in the references listed in Table 1. The N5 location was a 30 m soil trench on the Hubbard Brook Experimental Forest. The N6 location was the Bartlett Experimental Forest. The N1 and N2 locations had been recently clearcut, and the M2 location had been whole-tree harvested. Soil textures were generally sandy loams except for the M1 and M2 locations, which were silt loams.

Field and laboratory methods

D_b samples for O horizons were generally obtained by the pin block method. Our pin block is a 13 × 13 cm square of 1.2 cm plywood penetrated by 20 stainless steel rods (3 mm diameter by 20 cm long)

spaced 2 cm apart in a 10 × 10 cm square. Oi material was removed, then the block was placed horizontally on the soil surface and the rods pushed downward through the O horizon. The block of soil containing the pins was excavated, inverted, and trimmed inward to the pins, thus sampling an area of 100 cm². Mineral soil was removed and the thickness of the O horizon was estimated to the nearest mm by averaging all four sides. At the N6 location, Oe, Oa, and A horizons were separated (Federer 1982), but at all other locations Oe and Oa horizons were pooled. On all locations except M2, 10 subsamples 5 m apart along a line were composited into one sample and five or six such samples were collected.

A small core sampler was used for mineral soil horizons at all locations except M2. This sampler had a diameter of 54.5 mm and a depth of 28.3 mm yielding a volume of 66.0 cm³. Three core subsamples from a horizon were composited into one sample. Mineral horizons were not sampled at location N6.

The M2 location was sampled to determine the effects of soil disturbance by whole-tree harvesting (Turcotte et al. 1991). Uncomposited pin block samples 15 cm deep were collected and divided into O horizon and mineral soil. Sampling was stratified into three classes of harvest disturbance based on the surface condition: undisturbed, organic mounds, and mineral mounds and ruts. Samples were collected from soils ranging in drainage class from poorly to well drained.

All samples were air dried and sieved. O horizon samples were sieved to 2, 6, or 12 mm depending on location and year of sampling. We now believe that 6 mm is the most satisfactory separation because it facilitates field-moist sieving for microbiological research, while still removing most roots, wood, and stones. Mineral horizons were sieved to the standard 2 mm. Coarse fragment volumes were accounted for as described in the Appendix. Air-dry water content was obtained by oven-drying subsamples at 80°C for O horizons and 105°C for mineral horizons. F_o was measured by loss on ignition for 3–5 h at 500–550°C.

Statistics

We fit eq. 3 to data using the Marquardt–Levenberg algorithm to choose the values of D_{bo} and D_{bm} that minimize the error sum of squares in $\log D_b$ (Kuo et al. 1992). The variance of D_b is strongly dependent on F_o , but this dependency is removed by the log transformation. This approach assumes no error in F_o . A 95% confidence interval around the parameter estimates was obtained as 1.96 times the standard error of the estimate. Overlapping confidence intervals suggest nonsignificant differences. More specific statistical conclusions are not warranted as the study was not designed specifically to test the theoretical equation.

Results

We fit eq. 3 to the measured F_o and D_b data from each location except N6. D_{bo} varied only from 0.10 to 0.13 Mg/m³

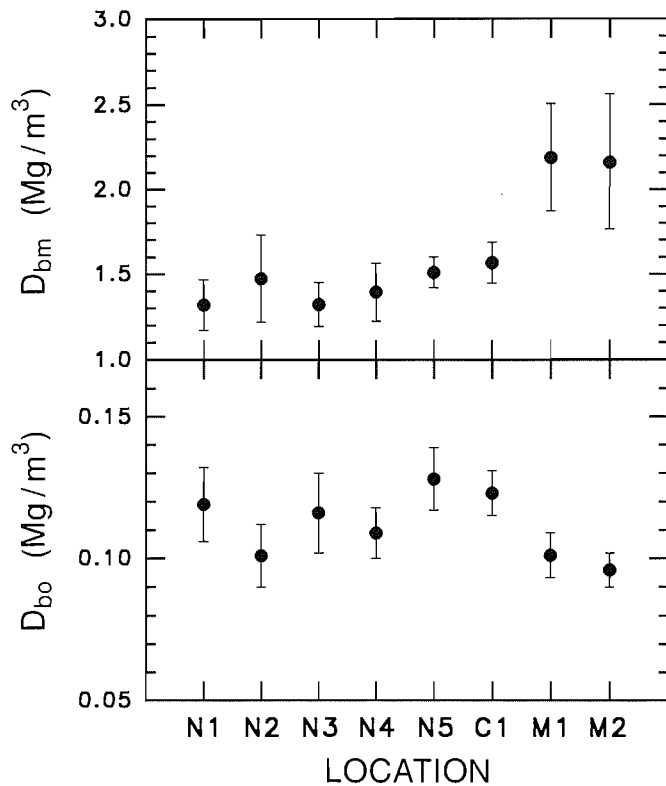


FIG. 1. Values of D_{bm} and D_{bo} by location as determined by fitting eq. 3 with 95% confidence intervals. Locations and number of samples are given in Table 1.

among all locations, though confidence limits were so narrow that slight but real difference among locations may exist (Fig. 1). D_{bm} ranged from 1.3 to 1.6 Mg/m^3 among the N locations and C1, though differences among these were not significant. There was no evidence of any trend with stand age among locations N1 through N5. Locations M1 and M2 had identical D_{bm} values of 2.2 Mg/m^3 , and confidence intervals that suggested they are distinctly different from the N and C1 locations. Apparently 20–30 samples from a location are adequate to evaluate the parameters in eq. 3 as long as samples are collected from all soil horizons.

To obtain a general relationship for till soils in the White Mountains of New Hampshire, we pooled data from locations N1 through N5 and obtained a fitted curve with $D_{bo} = 0.111 Mg/m^3$ and $D_{bm} = 1.450 Mg/m^3$ (Fig. 2). The usual linear graph of D_b versus F_o shows a highly nonlinear relation and nonhomogeneous variance in D_b . Plotting $\log D_b$ versus $\log F_o$ homogenizes the variance, helps to linearize the relationship, and shows relative rather than absolute error (Fig. 2).

Samples from the recently harvested M2 location were stratified into three disturbance classes: organic mounds, mineral mounds and ruts, and undisturbed. In spite of disturbance, these data did not differ from the curve for the nearby mature forest at location M1 (Fig. 3). Fitted parameters for all M2 data combined were virtually identical to location M1 (Fig. 1). Periodic freeze–thaw and wet–dry cycles over the 30 months since harvest may have compensated for any possible compaction or other alteration of D_b – F_o relationship (Holman et al. 1978). Mixing caused by the logging disturbance apparently fits the assumption of additive mineral and organic volumes.

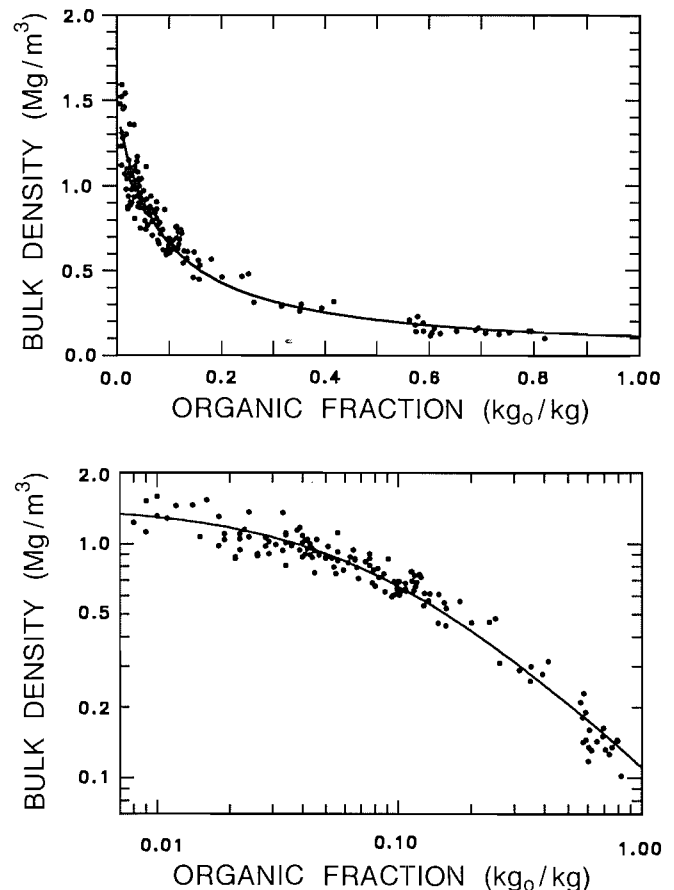


FIG. 2. Bulk density as a function of organic fraction, together with fitted eq. 3 for pooled locations N1 through N5. Upper graph is linear; lower graph is log–log.

The product of F_o and D_b is the organic density, or organic mass per soil unit volume. Because of the inverse relationship between F_o and D_b , organic density is nearly constant at 0.1 Mg_o/m^3 when $F_o > 0.1$ (Fig. 4). For the N6 location, data were collected separately for Oe, Oa, and A horizons. Organic density varied slightly among these subhorizons when compared with lumped O horizons at the same F_o (Fig. 4). Oe horizons had a slightly lower D_b and organic density, and Oa horizons had a slightly higher D_b and organic density.

At location C1, D_b was measured in four pits by both the core method and a whole pit volume method. Each 0.5×1.0 m pit was quantitatively excavated by O, A, B1, and B2 horizons using methods described by Huntington et al. (1989). Bulk densities determined by both the core and the whole pit volume methods fell on the same D_b – F_o curve indicating that there was no difference between the methods.

Discussion

Bulk density and organic fraction

The relationship of D_b to F_o in New England forest soils follows a remarkably smooth curve over the whole range of F_o from 0.01 to 1.0. A theoretical relationship, which is based on the assumption of additive volumes of mineral matter and organic matter, fits measured data quite satisfactorily. This relationship, shown in eq. 3, has only two parameters, D_{bo} and D_{bm} .

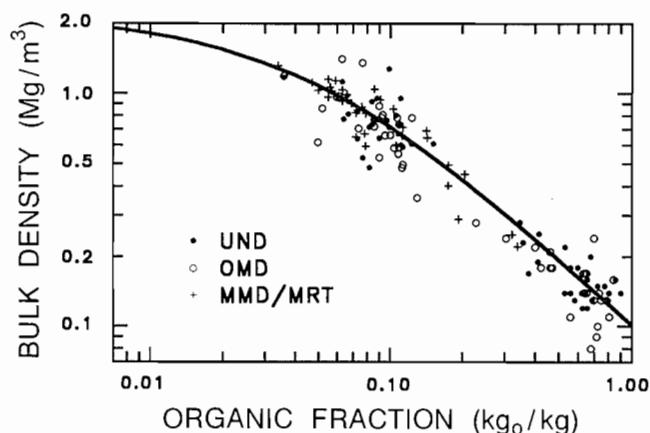


FIG. 3. Bulk density as a function of organic fraction for location M2 by disturbance class, and curve of eq. 3 as fitted to location M1. UND, undisturbed; OMD, organic mound; MMD–MRT, mineral mound or rut.

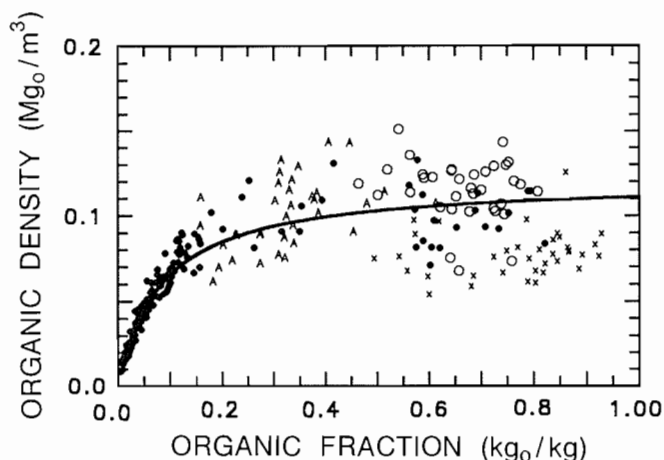


FIG. 4. Organic density as a function of organic fraction. Fitted curve and solid circles are for locations N1 through N5. Data points shown with the letters X, O, and A are Oe, Oa, and A horizon data, respectively, for location N6.

Curtis and Post (1964) collected data for acid till soils under northern hardwood forests in Vermont. For their data, eq. 3 with $D_{bo} = 0.155 \text{ Mg/m}^3$ and $D_{bm} = 1.308 \text{ Mg/m}^3$ gives virtually the same curve as their quadratic log-log regression (Fig. 5).

For our data from forest soils throughout New England, D_{bo} is close to 0.11 Mg/m^3 , regardless of horizon, cover type, stand age, disturbance, or soil texture. The higher D_{bo} of 0.16 Mg/m^3 from Curtis and Post (1964) for the same soils and region may be caused by their use of core samplers for O horizons and consequent compression.

For our soils, D_{bm} did not depend on horizon, cover type, stand age, or disturbance, but did appear sensitive to soil texture. We obtained values around 1.4 Mg/m^3 for coarser-textured sandy loams, and 2.2 Mg/m^3 for finer silt loams. Data of Curtis and Post (1964) for "mainly sandy loams" are fit with $D_{bm} = 1.3 \text{ Mg/m}^3$. Further work is necessary to determine the relation of D_{bm} to texture.

Jeffrey (1970) first suggested that a universal D_b – F_o relation might be applicable to all soils. He compiled data from the literature on agricultural, forest, and wetland soils from around the world. Jeffrey's data are fit by eq. 3 with $D_{bo} =$

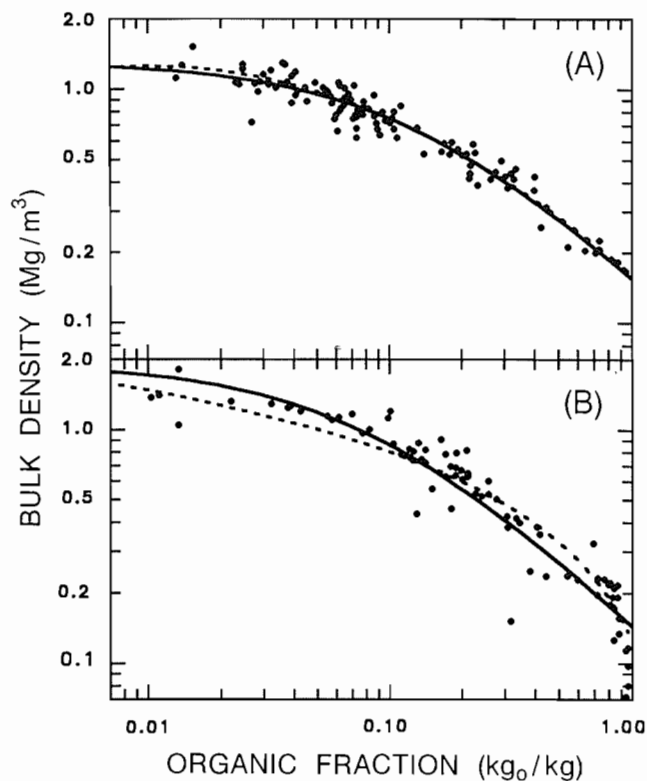


FIG. 5. Bulk density as a function of organic fraction for two data sets from the literature. Solid lines are eq. 3 with $D_{bm} = 1.308 \text{ Mg/m}^3$ and $D_{bo} = 0.155 \text{ Mg/m}^3$ for Curtis and Post (1964) (A), and $D_{bm} = 1.928 \text{ Mg/m}^3$ and $D_{bo} = 0.144 \text{ Mg/m}^3$ for Jeffrey (1970) (B). Broken lines are the equations given in the original papers.

0.14 Mg/m^3 and $D_{bm} = 1.93 \text{ Mg/m}^3$ (Fig. 5). The curve shape differs somewhat from Jeffrey's log-linear expression. At a given F_o , Jeffrey's bulk densities are generally 20–50% higher than ours. The discrepancy may partly be attributed to the paucity of forest soils in his sample.

For fitting eq. 3 to a specific location, samples from a full range of F_o are needed if D_{bm} and D_{bo} are to have realistic values. If samples of high F_o are missing, D_{bo} should probably be assumed. If samples of low F_o are missing, D_{bm} should be assumed. The lack of samples with $F_o < 0.04$ for the M1 and M2 locations may have contributed to their higher values of D_{bm} . Only 20–30 core and pin block samples seem sufficient to characterize the D_b – F_o relationship for a location. Thereafter, D_b for individual mass or "grab" samples can be estimated from F_o determined from loss on ignition.

The assumption of separable organic and mineral volumes, each with its own constant D_b , apparently is valid for our soils. This implies that no matter how organic matter and mineral matter are mixed, each mass component has its own associated volume and there is no interaction between the components. It is difficult to reconcile this conclusion with the normal expectation that organic matter increases porosity of mineral soils by promoting aggregation (Brady 1984). Our soils are coarse-textured for the most part and have single-grained to fine-granular structure. Equation 3 may not work well in finer-textured soils where organic matter promotes coarser structures, or in compacted or cemented horizons, but it still provides a theoretical basis from which deviations can be discussed.

TABLE 2. Exchangeable calcium in moles per unit soil mass and mass per unit area for Norberg Creek in the Turkey Lakes Watershed, Ontario, and calculated calcium charge fraction of CEC, CEC charge per unit organic mass, organic fraction, bulk density, and effective horizon thickness

Horizon	M_{Ca}/m_s (mmol Ca/kg)	M_{Ca}/A (kg Ca/ha)	M_{Ca}/M_c (mol _c Ca/mol _c CEC)	M_{Ca}/m_o (mol _c CEC/kg _o)	F_o (kg _o /kg)	D_b (Mg/m ³)	T_s (cm)
L	78.2	19	0.49	0.43	0.737	0.031	2.0
F	74.4	57	0.56	0.41	0.647	0.064	3.0
H	63.3	86	0.73	0.55	0.319	0.170	2.0
Ae	9.8	101	0.30	1.03	0.064	0.80	3.2
Bhf1	11.2	108	0.21	1.06	0.101	1.00	2.4
Bhf2	5.9	121	0.13	1.54	0.061	0.80	6.4
Bf	2.5	341	0.12	0.74	0.058	1.00	33.6
IIBC	0.8	87	0.09	0.71	0.024	1.40	20.0
IIC	0.7	64	0.10	0.78	0.018	1.50	14.4

NOTE: Data are from Morrison (1990). CEC, cation exchange capacity.

TABLE 3. Organic density and total N, available P, and exchangeable K per unit organic mass for the Turkey Lakes Watershed, Ontario

Horizon	Organic density (Mg _o /m ³)		Total N (kg N/Mg _o)		Available P (kg P/Mg _o)		Exchangeable K (kg K/Mg _o)	
	NC	WL	NC	WL	NC	WL	NC	WL
L	23	19	25	23	0.27	0.20	0.67	0.80
F	41	34	28	29	0.33	0.26	0.74	0.84
H	54	74	40	36	0.27	0.14	0.86	1.06
Ae	51	65	40	46	0.12	0.10	1.05	1.04
Bhf1, Bf1	102	52	42	45	0.04	0.08	0.81	0.47
Bhf2, Bf2	49	61	58	37	0.06	0.07	0.90	0.32
Bf	58	—	32	—	0.07	—	0.34	—
IIBC	33	56	30	33	0.18	0.11	0.33	0.35
IIC	26	19	33	29	0.29	0.35	0.44	0.31

NOTE: Data are calculated from Morrison (1990). NC, Norberg Creek; WL, Wishart Lake.

Organic density

Organic mass per unit soil volume is "organic density" and is the product $F_o D_b$. When $F_o > 0.1$, organic density is nearly constant around 0.1 Mg_o/m³ for our forest soil horizons. Each centimeter of thickness of such horizons therefore contributes about 10 Mg_o/ha. This leads to the important conclusion that any property that is directly proportional to mass of organic matter will also be directly proportional to horizon thickness when $F_o > 0.1$.

Constant organic mass per unit soil volume was found earlier for Histosols by Lynn et al. (1974) and Gosselink et al. (1984). Lynn et al. (1974) concluded that, for Histosols, "...organic soil fabric is an open, skeletal framework of organic material in which mineral matter occupies interstitial space but does not alter the bulk volume." In other words, the volume, V_m , contributed by adding mineral particles to pure organic soil is negligible, and thus $D_b = D_{bo}/F_o$ (Gosselink et al. 1984). On the contrary, eq. 3 assumes that the mineral mass contributes its own volume.

Averaging over samples

The standard procedure for calculating forest soil properties for a horizon on a volume basis multiplies average sample concentration, m_x/m_s , by average D_b , m_s/V , where m_x is the mass of some material, m_s is the soil mass, and V is the soil volume. This averaging procedure is incorrect when the individual samples from the horizon vary in F_o and thus in bulk

density: $\overline{m_x/m_s} \times \overline{m_s/V}$ is not equal to the correct volume average, $\overline{m_x/V}$, which is $\overline{m_x/m_s} \times \overline{m_s/V}$. For instance, for three samples having F_o values of 0.2, 0.4, and 0.6 and bulk densities given by eq. 3 with the lumped N1 to N5 parameters, the correct average F_o using $\overline{m_o/m_s} \times \overline{m_s/V}$ is 0.097 Mg_o/m³, while $\overline{m_o/m_s} \times \overline{m_s/V}$ is 0.113 Mg_o/m³, a 16% error. This same error would occur when averaging any property that was proportional to F_o . The proper way to average over samples is on a volume basis, not a mass basis. If samples were not collected volumetrically, proper averaging can be done by using eq. 3 to estimate each sample's D_b from its loss on ignition. Then the product of concentration and the estimated D_b can be used to average.

Presentation of results

In the *Canadian Journal of Forest Research* for 1990, eight articles compare soil nutrients among horizons and locations. Of these, two give concentrations only on the basis of soil mass, while the other six give values on both mass and area bases. However, neither of these bases allow complete and satisfactory interpretation of similarities or differences among horizons and soils. Ideally each source of variation should be analyzed and expressed separately.

We illustrate with the example of an exchangeable cation where the cation exchange capacity is produced primarily by organic matter. The moles of exchangeable cation, M_x , per unit area, A , can be written as

$$[4] \quad \frac{M_x}{A} = \frac{M_x}{M_c} \frac{M_c}{m_o} F_o D_b T_s$$

where M_c is moles of exchange capacity, m_o is organic mass, and T_s is the effective thickness (corrected for coarse fragments; see Appendix). The amount of exchangeable cation in a horizon or the whole soil depends on the five separate properties on the right side of eq. 4: mole fraction of exchange, exchange capacity per unit organic mass, organic fraction, bulk density, and effective thickness, respectively. For other soil properties, the first two or three terms may be combined.

For many purposes, expression of nutrient content on a volume basis is especially useful (Gosselink et al. 1984). The volume basis represents the amount of nutrient that is available to a unit length or area of root, whether the root is growing toward the nutrient or the nutrient is diffusing toward the root. For leaching studies, volume is the appropriate basis to relate to volume of water, whether static (concentration) or dynamic (flux). The volume basis is obtained by dividing eq. 4 by T_s .

We have used exchangeable Ca data of Morrison (1990) as an illustration of eq. 4. Morrison's paper is typical because results were reported only on the bases of soil mass and area. He provided values of F_o by horizon, moles of exchangeable Ca per unit soil mass (M_{Ca}/m_s), mass of exchangeable Ca per unit area (m_{Ca}/A), coarse fragment volume, and thickness for two locations. We back-calculated D_b from his other data. M_{Ca}/m_s is very high in the Oi, Oe, and Oa horizons, then declines rapidly with depth (Table 2). This depth variation arises primarily from variation in F_o and only secondarily from the Ca fraction of the exchange, M_{Ca}/M_c (Table 2). The exchange capacity per unit organic mass, M_c/m_o , varies only by a factor of 3 over all horizons. Variation in exchangeable Ca among horizons on both mass and area bases is seen to depend primarily on F_o and on T_s , respectively, neither of which has anything to do with the Ca itself.

Nutrient-related properties of northern forest soils that are closely tied to mass of organic matter include nitrogen (Gorham 1953; Federer 1984), nitrogen mineralization (Federer 1983), cation exchange capacity, and buffering capacity (Federer and Hornbeck 1985; Magdoff et al. 1987). Expression of such properties on an organic mass basis (e.g., kg N/Mg_o) separates the effect of organic density from concentration of the property in the organic matter (Table 3). For Morrison's (1990) locations, organic density varied little with depth except in the uppermost and lowermost horizons (Table 3). Variation of total N, available P, and exchangeable K per unit organic mass varied little between locations for a given horizon. Further analysis would be needed to determine if the small differences were real and could be interpreted. Variation with depth was gradual (Table 3). N fraction of organic matter peaked in the middle horizons. P in the deep horizons was probably not organic, but the P fraction of organic matter was greatest in the shallowest horizons. The maximum in exchangeable K per unit organic mass was in middle horizons. If generalizations about soil properties are to be made, the important role played by organic density should be explicitly quantified.

Conclusions

Bulk density is closely related to organic fraction over the wide range of organic fractions found in New England forest soils. A theoretical assumption that mineral volume and

organic volume are additive in any mixture leads to a useful, two-parameter expression of the relationship. The parameters do not vary much among forest soils and may be fitted from 20 to 30 bulk density samples from any location. Proper averaging over mass samples requires the bulk density of each sample. Bulk density can be estimated for each sample from its organic fraction (loss on ignition) and eq. 3.

The close, inverse relationship between organic fraction and bulk density in forest soils needs to be recognized and utilized in presentation and interpretation of results. Organic density in New England forest soils is nearly constant at about 0.1 Mg_o/m³ over the range of organic fractions from 0.1 to 1.0. This could be useful for estimating nutrient contents of O and A horizons. For comparison of nutrients related to organic matter among horizons or locations, the amount per unit organic mass and the organic density should be interpreted separately.

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Appendix: Coarse fragments

Bulk density sampling often effectively divides soil coarse fragments into two size classes: smaller fragments that are included in volumetric bulk density samples and larger boulders and roots that are excluded from such samples. Furthermore, organic coarse fragments have a different density than mineral coarse fragments. This appendix shows algebraically how to account for these effects.

The term “soil” usually is defined as “fine earth” or material passing a sieve of some arbitrary size. For mineral horizons, a 2 mm sieve has long been the standard, but for O horizons we use a larger sieve size of 6 mm so that field moist samples can be sieved readily. Material not passing through the sieve is called “coarse fragments” and is excluded from “soil”. Effective thickness, T_s , of a horizon or layer is defined here as the thickness of the layer if coarse fragments are excluded.

The volume fraction of smaller coarse fragments is often measured on samples collected for bulk density, whereas the volume fraction of the large fragments is estimated separately. In a bulk density sample of volume, V_t , the volume fractions of mineral coarse fragments, f_m , and the organic coarse fragments, f_o , are

$$[A1] \quad f_m = \frac{\left(\frac{M_m}{\rho_m}\right)}{V_t}$$

$$[A2] \quad f_o = \frac{\left(\frac{M_o}{\rho_o}\right)}{V_t}$$

where M_m and M_o are the masses of mineral and organic coarse fragments in the sample, respectively, and ρ_o and ρ_m are the particle densities of these coarse fragments. The value of ρ_m is usually assumed as 2.65 Mg/m³, the average density of rock minerals commonly found in soils. The solids density of organic matter is about 1.3 Mg/m³ (DeVries 1963), but organic coarse fragments are porous. A value of $\rho_o = 0.7$ Mg/m³ seems appropriate, but we do not know of a citation. Bulk density (D_b) for the sample is then calculated as

$$[A3] \quad D_b = \frac{m_s}{[V_t(1 - f_o - f_m)]}$$

where m_s is the mass of fine earth in the sample.

When the bulk density sampling excludes larger coarse fragments, the fractions of the total soil volume, V_T , occupied by the large organic and mineral coarse fragments, f'_o and f'_m respectively, must be estimated separately. Then, because

$$[A4] \quad \frac{V_s}{V_t} = (1 - f_o - f_m)$$

and

$$[A5] \quad \frac{V_t}{V_T} = (1 - f'_o - f'_m)$$

the effective thickness of the horizon, T_s , is

$$[A6] \quad T_s = T(1 - f_o - f_m)(1 - f'_o - f'_m)$$

where T is the measured thickness. The stone volume fraction, f'_m , is difficult to estimate or measure, but may be 0.3 to 0.5 for some till soils. Error in f'_m may be the largest single source of error in estimating soil properties on a volume or area basis. The large root fraction, f'_o , is also difficult to estimate, but may be negligible.