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DIVISION S-7—FOREST & RANGE SOILS

Carbon to Organic Matter Ratios for Soils in Rocky Mountain Coniferous Forests

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ABSTRACT

Vegetation type, soils, climate, and conversion ratios influence estimates of terrestrial C. Our objectives were to (i) determine carbon to organic matter (C/OM) ratios for brown cubical rotten wood, litter, surface humus, soil wood, and mineral soils; (ii) evaluate the validity of using 0.58 and 0.50 ratios for estimating C in mineral and organic soil components, respectively; and (iii) determine if C/OM relationships were applicable across broad geographic areas. The study sites were located from the southern to northern Rocky Mountains. They differed in vegetation, soil parent material, and climate. The C/OM regression slopes we developed for organic components were quite consistent and relatively constant across vegetation types ranging from 0.43 to 0.51 and were similar to the 0.50 traditional ratio. The C/OM regression slopes for mineral soils ranged from 0.16 to 0.48 depending on vegetation type. These slopes were lower than the 0.58 ratio often applied. The reliability of simple ratios when used in estimating C as a function of organic matter is often overestimated. Error and bias can be introduced into C estimates when using simple ratios. This study refined C/OM regressions for mineral soils and provided regressions for organic soil components. Information developed in this study can be applied to improve regional and global C assessments.

ESTIMATES of global C budgets show a missing C sink exists (Bolin et al., 1979; Eswaran et al., 1993; Post et al., 1982, 1990; Tans et al., 1990). One implication of this missing sink is that if global warming does occur, the missing sink may become a C source. Various theories exist on the location of this C sink. For terrestrial ecosystems, studies have estimated that soil C pools can store between 700 to 3000 Pg C (Bouwman and Leemans, 1995). These estimates vary depending on (i) what ecosystem components are included, (ii) the accuracy of conversion factors, (iii) the variation among vegetation, mineral, and organic soils, and (iv) the rate and extent of organic matter decomposition (Bouwman and Leemans, 1995; Eswaran et al., 1993; Hendrickson, 1990; Pollard, 1982; Post et al., 1982, 1990).

Many C containing ecosystem components may not be considered in global C estimates. Recent summarizations of global C estimates (Bouwman and Leemans, 1995) concentrated on C only located in the mineral-soil fraction. The estimates did not mention the amount of C stored in forest soil components such as brown cubical rotten wood (rotten woody material on the forest floor) and soil wood (rotten wood and decayed roots incorporated into mineral soil), which can make up 30 to 60% of the forest floor in northwest forests (Graham et al., 1994). In addition, Bouwman and Leemans (1995) did not address the amount of C in plant litter (slightly decomposed organic material, O_i horizon) and surface humus (intermediate and highly decomposed organic material, O_e and O_a horizons) (Buol et al., 1989; Soil Survey Staff, 1992). Because 30% of the USA is covered by forests (Bailey, 1995), the omission of these organic soil components could cause part of the discrepancy in C estimates.

Another potential source of error in estimating global C is the use of inappropriate organic matter to C conversion factors. Many forest soil C contents have been determined by loss-on-ignition (LOI). Loss-on-ignition is a gravimetric procedure based on weight loss due to the oxidation of organic matter in mineral soil and other organic components via dry combustion (Ball, 1964; Donkin, 1991; Schnitzer, 1982). Organic matter content is converted to C content by using a common C/OM ratio of 0.58 (Gortner, 1916; König, 1911). However, when this C/OM ratio is used, it is often assumed to be the same for all soil and vegetation types. Various studies have shown that this ratio is not the same and that it may vary widely depending on vegetation type, parent material, soil depth, and climate (Ball, 1964; Donkin, 1991; Lunt, 1930; Nelson and Sommers, 1982; Waksman and Stevens, 1930). Another conversion factor often used for estimating C from organic biomass is 0.50 (Broadbent, 1953; Linder and Axelsson, 1982). Better quantitative C estimates could be obtained by using separate C/OM ratios for different vegetation, soil types, and organic components.

Our objectives were to develop more precise C/OM ratios for certain soil organic and mineral components so they may be applied to improve C estimates, to evaluate the validity of using 0.58 and 0.50 ratios for estimating C in mineral and organic soil components, and to determine the extent to which C/OM ratios are applicable across broad geographic areas.

MATERIALS AND METHODS

Site Selection

To test if C/OM ratios could be used across a broad area, study areas represented four soil parent materials and three climatic regimes (Table 1). The wettest and most productive site was a western hemlock–queencup beadlily [*Tsuga heterophylla* (Raf.) Sarg.; *Clintonia uniflora* (Schult.) Kunth] (WH/CLUN) habitat type (Cooper et al., 1991) on the Priest River Experimental Forest in northern Idaho. A cold-dry subalpine fir–dwarf huckleberry [*Abies lasiocarpa* (Hook.) Nutt.; *Vac-*

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Abbreviations: C/OM, carbon to organic matter ratio; LOI, loss-on-ignition; WH/CLUN, western hemlock–queencup beadlilly; SAF/VASC, subalpine fir–dwarf huckleberry; PP/FEAR, ponderosa pine–Arizona fescue; PP/QUGA, ponderosa pine–gambel oak.

Table 1. Description of selected locations.

Habitat type†	Parent material‡	Elevation	Total precipitation	Snow fall	Avg. annual air temperature	Time of year precipitation occurs	Climate regime
		m	cm		°C		
WH/CLUN	Ash–Belt	760–1280	71–152	262	4–10	fall–winter	cool–wet
SAF/VASC	Volcanic	2130–2190	28–74	686	−4–2	fall–winter	cold–dry
PP/FEAR	Limestone	2300–2500	52–60	112	4–6	winter–spring	warm–dry
PP/QUGA	Basalt	2300–2500	52–60	112	4–6	summer–fall	warm–dry

† Habitat types are, in northern Idaho, WH/CLUN = western hemlock–queencup beadlily (Cooper et al., 1991); in western Montana, SAF/VASC = subalpine fir–dwarf huckleberry (Pfister et al., 1977); and in northern Arizona, PP/FEAR = ponderosa pine–Arizona fescue and PP/QUGA = ponderosa pine–gambel oak (Larson and Moir, 1986).

‡ Parent materials (Alt and Hyndman, 1989; Hunt, 1972) are Basalt, black volcanic rock rich in Fe, Ca, and Mg and composed primarily of augite and plagiocalase feldspar; Volcanic (Rhyolite), lava or shallow intrusion, fine grained, with composition equivalent to granite; Limestone, sedimentary rock or surface deposit of calcium carbonate; Belt, mildly metamorphosed, sedimentary rocks, including argillites, siltites, quatzites, and dolomites; and Ash, fine shreds of lava blown from Mount Mazama.

cinium scoparium Leib.] (SAF/VASC) habitat type (Pfister et al., 1977) was on the Deerlodge National Forest in western Montana. Two warm-dry sites were selected in northern Arizona: a ponderosa pine–Arizona fescue (*Pinus ponderosa* Douglas ex P.&C. Lawson; *Festuca arizonica* Vasey) (PP/FEAR) habitat type (Larson and Moir, 1986) on the Kaibab National Forest and a ponderosa pine–gambel oak (*Quercus gambelli* Nutt.) (PP/QUGA) habitat type (Larson and Moir, 1986) on the Coconino National Forest (Table 1).

The following criteria were used for developing a list of potential sites that had similar biophysical characteristics from each habitat type: (i) harvested and nonharvested sites near each other with similar aspects, slopes, elevation, geology, and climate; (ii) nonharvested sites at least 5.0 ha in size consisting of late-seral and old vegetation with no direct human activity; and (iii) sites harvested within the last 5 to 10 yr that were at least 5.0 ha in size with the remaining woody residue tractor piled. From each list, three nonharvested and three harvested sites were randomly selected within each habitat type.

Data Collection and Laboratory Analysis

Twelve sampling points were systematically located (20-m spacing) on a random transect bisecting ≈5.0 ha of each site. Forest soil components (brown cubical rotten wood, soil wood, litter, surface humus, and mineral soils) were sampled by extracting a soil core 10 cm in diameter by 30 cm deep. Soil components were separated and placed in cloth bags. In cases where a specific soil component was not in the soil core, a random sample of the component was gathered within a 13.5-m^2 plot.

To estimate C/OM ratios, we conducted LOI (Ball, 1964) and organic C analyses on soil components for both the harvested and nonharvested sites. This aspect of the study was included to test if management activities influence C/OM ratios. Soils were air dried for 4 to 8 d and then oven dried for 24 h at 60°C. Samples were then sieved using screens with 2-mm openings during which coarse fragments >2 mm in diameter and roots were removed. Decayed wood and decayed roots were combined for determining the C/OM ratios for soil wood. The 12 samples from each soil component were physically mixed into four composites for each site (Ruark and Zarnoch, 1992). To ensure that LOI estimates were not biased by loss of carbonates, mineral soils were tested for carbonates using 0.01 *M* hydrochloric acid (Soil Survey Staff, 1992).

The C, H, and N autoanalyzer (CHN-600, LECO Corporation[1], St. Joseph, MI) was used to determine total C of organic and mineral soil components. Organic matter concentrations for soil components were determined using LOI. Each sample was weighed and placed in a muffle furnace at 375°C for 16 h (Ball, 1964). Samples were removed from the furnace and reweighed. Organic matter concentrations were calculated from the weight differences and displayed as a proportion.

[1] The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Statistical Analysis

Analysis of variance for a randomized complete-block design was the primary analytical technique (Steele and Torrie, 1960). The four composites were used to determine the mean C/OM ratio for each disturbance from each habitat type. For comparing ratios between nonharvested and harvested sites, four habitat types, two disturbances (nonharvested and harvested), and three replications (sites) were used in a split block design. This design increased the power of detecting differences between nonharvested and harvested sites. This analysis was done to determine if management activities affected C/OM ratios. Nonharvested and harvested data within each habitat type were combined if no differences were detected. Analysis of variance was conducted to determine if significant differences in C/OM ratios occurred among habitat types and among soil components within each habitat type. Because data from nonharvested and harvested sites were combined, eight composites were used to determine the mean C/OM ratio for each replication (n = 3) and habitat type (n = 4) combination. Scheffe's multiple range test (Steele and Torrie, 1960) was used to separate main effects. Before conducting the analysis, C proportional data were transformed using the square root of the arcsin.

Regression analyses were used to describe the relationship between C and organic matter. Simple linear regression was conducted with the data determining the Y intercept. A second regression analysis was conducted forcing the Y intercept through the origin, although we knew that the statistics produced by this procedure would be biased. We chose this method to compare the results from this study to other studies that developed simple conversion ratios.

RESULTS

Apparently because of parent material and leaching, no carbonates were detected when the forest soils were tested with hydrochloric acid (Buol et al., 1989; Pritchett and Fisher, 1987; Soil Survey Staff, 1992). Therefore, we attributed LOI weight loss to organic C. Carbon to organic matter ratios in both harvested and nonharvested sites ranged from 0.43 to 0.56 in the organic components (brown cubical rotten wood, litter, surface humus, and soil wood). Mineral soil C/OM ratios on the same sites ranged from 0.13 in the SAF/VASC to 0.52 in the PP/FEAR habitat type. The only difference ($P \leq 0.05$) detected in C/OM ratios occurred in the SAF/VASC habitat type. The deep mineral C/OM ratio for nonharvested sites was 0.13, and the harvested sites C/OM ratio was 0.17. Because many components had similar C/OM ratios between harvested and nonharvested sites, we pooled the data by soil component within each habitat type.

The C/OM ratios for the litter, soil wood, and brown cubical rotten wood among habitat types were not different (Table 2). The C/OM ratios for surface humus and shallow mineral soil in the PP/FEAR were significantly ($P \leq 0.05$) higher than the ratios for the same soil components in the other habitat types. Similarly, the C/OM ratio for deep mineral soil for the PP/FEAR (0.36) was significantly greater than the ratio for SAF/VASC (0.15; Table 2). Within each habitat type, except for PP/FEAR, no differences in C/OM ratios were detected among the organic soil components. However, more differences in C/OM ratios were detected between the shallow and deep mineral soil components within each habitat type.

Depending on the similarities in C/OM ratios both within and among habitat types, data were combined. Data for organics (brown cubical rotten wood, litter, soil wood, and surface humus) were combined for all habitat types except PP/FEAR. Because some C/OM ratios were significantly higher in the PP/FEAR compared with the other habitat types, data for the PP/FEAR were analyzed separately.

With the combined data, equations for predicting C as a function of organic matter were developed (Fig. 1 and 2). This analysis showed a highly significant relationship ($P = 0.0001$) between C and organic matter for all soil components. For the combined habitat types (PP/QUGA, SAF/VASC, and WH/CLUN), the variation in C (r^2) explained by organic matter ranged from 0.64 for deep mineral soils to 0.86 for organics (Fig. 1). As noted earlier, the uniqueness of the PP/FEAR habitat type necessitated developing separate regression equations. These relationships were also highly significant ($P = 0.0001$). The variation in C explained by organic matter ranged from 0.63 in deep mineral soils to 0.82 in the organics (Fig. 2). Comparing the two regression methods, the slopes for the regression equations for mineral soils produced in this study were lower than the traditional slope of 0.58 (Gortner, 1916; König, 1911; Fig. 1 and 2).

When the C to organic matter regressions were forced through the origin, the variation in C explained by organic matter improved, compared with allowing the data to set the Y intercept (Table 3). In addition, this traditional method of expressing C/OM ratios can significantly change the slope (ratio) of the relationship. For example, in this study, the slope for the organics in the PP/FEAR habitat type significantly ($P \leq 0.05$) increased (from 0.428 to 0.521) when the regression was forced through the origin (Table 3).

DISCUSSION

This study revealed that ratios of organic matter to C can be influenced not only by forest soil component but also by the methods used to calculate the ratios. For the most part, our regression slopes for the organic components of forest soils were quite consistent and relatively constant across divergent habitat types of the Rocky Mountains. However, the slopes generated for soils in the PP/FEAR habitat type of northern Arizona did not follow this trend. The slopes for organics were as low as 0.42, lower than the 0.50 ratio that is often applied to organic components (Broadbent, 1953; Linder and Axelsson, 1982).

The regression slopes for converting organic matter to C for mineral soils (0.16 to 0.48) were also lower than the ratio (0.58) that is often applied to mineral soils (Gortner, 1916; König, 1911). If simple ratios are calculated instead of regressions, additional error and bias can be introduced. This study showed that nearly a 10%

Table 2. Carbon to organic matter ratios by soil component and habitat type.

	Habitat type†							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
Soil components	Ratio	SE‡	Ratio	SE	Ratio	SE	Ratio	SE
	Proportion							
BCR§	x¶ 0.51ab	0.01	x 0.51a	0.01	x 0.49a	0.01	x 0.51a	0.01
Litter	x 0.53ab	0.01	x 0.46a	0.02	x 0.49a	0.02	x 0.51a	0.01
Surface humus	x 0.58a	0.02	y 0.46a	0.02	y 0.46a	0.02	y 0.48a	0.01
Soil wood	x 0.51ab	0.01	x 0.46a	0.03	x 0.50a	0.01	x 0.51a	0.01
Shallow mineral§	x 0.47b	0.02	y 0.26b	0.05	y 0.24b	0.01	y 0.20b	0.02
Deep mineral§	x 0.36c	0.02	xy 0.22b	0.06	xy 0.17b	0.01	y 0.15c	0.01

† Habitat types are, in northern Arizona, PP/FEAR = ponderosa pine–Arizona fescue and PP/QUGA = ponderosa pine–gambel oak (Larson and Moir, 1986); in northern Idaho, WH/CLUN = western hemlock–queencup beadlily (Cooper et al., 1991); and in western Montana, SAF/VASC = subalpine fir–dwarf huckleberry (Pfister et al., 1977).
‡ SE = standard error of the mean.
§ BCR = brown cubicle rotten wood; shallow mineral is 0 to 10 cm deep; deep mineral is 10 to 30 cm deep.
¶ Comparisons of statistical significance ($P \leq 0.05$) among habitat types are x and y and among soil components are a, b, and c.

difference in C could be realized between the two methods (Table 3).

Simple C/OM ratios (Donkin, 1991; Grigal and Ohmann, 1992; Huntington et al., 1989; König, 1911; Lunt, 1930) not only introduce error but also exaggerate the reliability of the ratio. We determined that ratios (regressions with zero intercepts) were biased and overestimated the variation in C explained by organic matter. In this study, using this technique, the r^2 for shallow mineral soil improved from 0.63 to 0.91, greatly overestimating the reliability of the predictions (Table 3).

The C/OM regression slopes produced in this study for mineral soils were lower than ratios reported in other studies. For example, studies conducted in the northeastern and southeastern USA reported C/OM ratios for spodosols of 0.48 to 0.52 (Huntington et al., 1989; Grigal and Ohmann, 1992). Slopes for mineral soils in the combined habitats from this study were much lower (0.16 to 0.24). In contrast, the slopes for the mineral soils (0.41 to 0.48) in the PP/FEAR habitat were similar to those reported for the spodosols. One explanation for this discrepancy could be the difference in mineral soil C concentrations among the studies (Donkin, 1991).

Carbon to organic matter ratios >0.40 for mineral soils were usually associated with soil C concentrations >5%. For example, Huntington et al. (1989) reported a C/OM ratio of 0.52 for spodosols in Pennsylvania. They reported C concentrations for the Bh soil horizon (a mineral horizon with an illuvial accumulation of organic matter) were >8%. Similarly, Grigal and Ohmann (1992) determined a C/OM ratio of 0.52 for mineral soils in the north-central Great Lake States. According to Huntington et al. (1989), C concentrations of mineral soils within this region were normally >8%. We experienced similar results. Average C concentrations in the shallow mineral soil of the PP/FEAR habitat type also exceeded 5% (6.1%), resulting in a 0.48 C/OM slope. Therefore, it appears, if mineral soil C concentrations are >5%, C/OM ratios tend to exceed 0.40. This trend may be influenced by parent material (Bohn et al., 1985; Borchers and Perry, 1991; Stevenson, 1986). The soils of the PP/FEAR habitat type may have stored more C compared with soils from the other habitat types. In contrast, for the combined habitat types in this study, the C concentrations for mineral soils were <5% and the C/OM regression slopes were 0.16 to 0.24. For similar soils, Donkin (1991) recommended a C/OM ratio of 0.28, similar to the ones we developed. A plausible explanation could be the climatic variation among habitat types. Subtle differences in climate influence decomposition, residence time, and chemical composition of

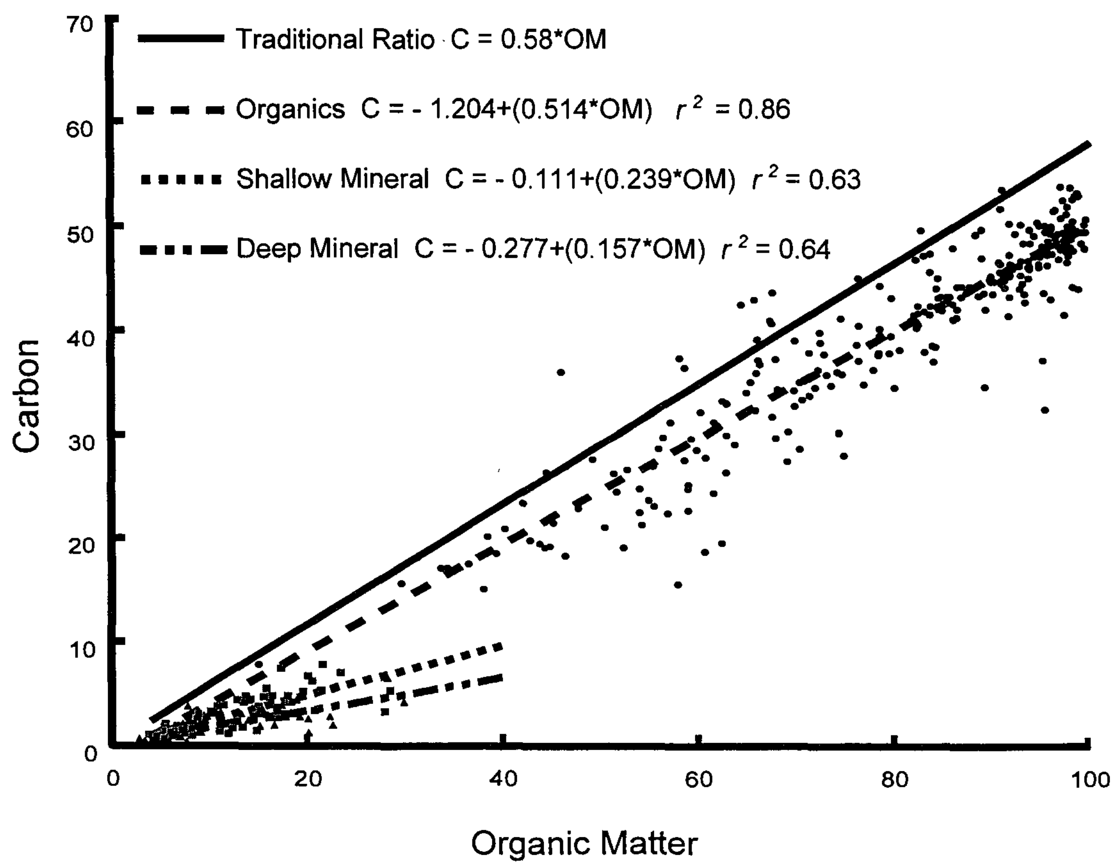

Fig. 1. Relationship between C and organic matter (OM) for combined forest habitat types (PP/QUGA, SAF/VASC, WH/CLUN) showing regression equations for organics (litter, brown cubical rotten wood, soil wood, and surface humus), shallow mineral (0–10 cm), and deep mineral (10–30 cm). Also included is the traditional ratio of 0.58 (Gortner, 1916; König, 1911). Habitat types are, in northern Idaho, WH/CLUN = western hemlock–queencup beadlily (Cooper et al., 1991); in western Montana, SAF/VASC = subalpine fir–dwarf huckleberry (Pfister et al., 1977); and in northern Arizona, PP/QUGA = ponderosa pine–gambel oak (Larson and Moir, 1986).

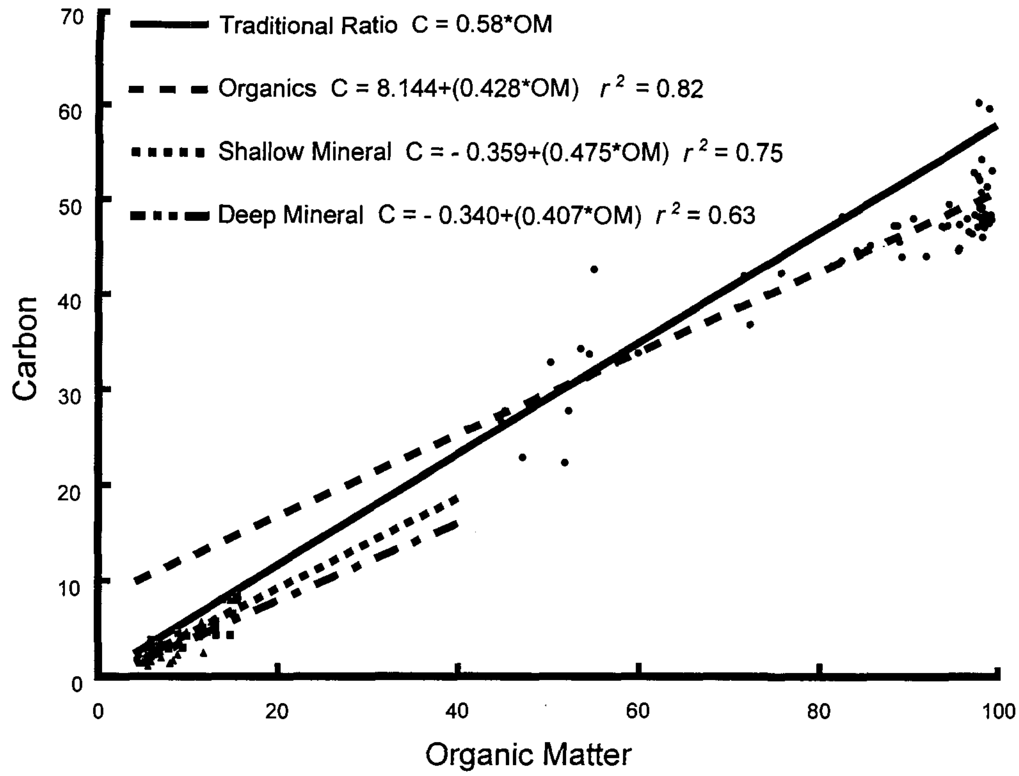

Fig. 2. Relationship between C and organic matter (OM) for the PP/FEAR habitat type showing regression equations for organics (litter, brown cubical rotten wood, soil wood, and surface humus), shallow mineral (0–10 cm), and deep mineral (10–30 cm). Also included is the traditional ratio of 0.58 (Gortner, 1916; König, 1911). In northern Arizona, PP/FEAR = ponderosa pine–Arizona fescue (Larson and Moir, 1986).

organic substrates, thereby affecting C/OM relationships (Baldock and Preston, 1995; Bohn et al., 1985; Stevenson, 1986).

We selected habitat types from divergent climate and moisture regimes found across a wide geographical area from the northern to the southern Rocky Mountains (Cooper et al., 1991; Larson and Moir, 1986; Pfister et al., 1977). Because different climatic conditions result in different decomposition rates and organic matter accumulation (Harmon et al., 1986; Harmon, 1992; Vogt et al., 1986), we initially assumed these C/OM ratios would vary by habitat type. Even with this diversity, no significant differences in C/OM ratios among habitat types for litter, soil wood, and brown cubical rotten wood were detected. The consistent C/OM ratios may relate to organic substrate composition at similar stages of decay (Harmon et al., 1986; Harmon, 1992).

Table 3. Regression statistics for predicting C as a function of organic matter by (i) forcing the *Y* intercept through the origin and (ii) allowing the data to determine the *Y* intercept.

Soil components	No intercept		Intercept	
	Slope	r^2	Slope	r^2
		Combined habitat types†		
Organics‡	0.499	0.99	0.514	0.86
Shallow mineral§	0.246	0.91	0.239	0.63
Deep mineral§	0.176	0.90	0.157	0.64
		PP/FEAR habitat type†		
Organics	0.521¶	0.99	0.428	0.82
Shallow mineral	0.444	0.96	0.475	0.75
Deep mineral	0.368	0.93	0.407	0.63

† Combined habitat types are WH/CLUN, SAF/VASC, and PP/QUGA. In northern Idaho, WH/CLUN = western hemlock–queencup beadlily (Cooper et al., 1991). In western Montana, SAF/VASC = subalpine fir–dwarf huckleberry (Pfister et al., 1977). In northern Arizona, PP/QUGA = ponderosa pine–gambel oak and PP/FEAR = ponderosa pine–Arizona fescue (Larson and Moir, 1986).
‡ Organics are brown cubicle rotten wood, woil wood, surface humus, and litter.
§ Shallow mineral is 0 to 10 cm deep; deep mineral is 10 to 30 cm deep.
¶ Slopes of the two regressions are significantly ($P \leq 0.05$) different.

Regression slopes for the organic soil components varied from 0.51 in the combined habitat types to 0.43 in the PP/FEAR. Lunt (1930) reported a C/OM ratio of 0.52 for deciduous forest litter in the north-central USA. This estimate was very comparable with our organic estimates. Without specific C/OM ratios available for soil wood and brown cubical rotten wood, a 0.50 conversion ratio for organics has been commonly applied to determine C content (Broadbent, 1953; Linder and Axelsson, 1982). We determined that regression slopes of 0.43 and 0.52 could be applied to improve C assessments.

Some disadvantages exist when using C/OM ratios, especially when mineral soils vary from site to site. However, ratios, and in particular regressions, provide information on C at a low cost and with nominal technical expertise required. Our findings show that by using C/OM regressions, C can be estimated across sites for the organic components, such as litter, soil wood, and brown cubical rotten wood if organic matter concentrations are known. Although we did not have differences in C/OM ratios among three habitat types, developing C/OM regressions for mineral soils by soil type would probably improve C estimates. However, C/OM regressions from this study provide better estimates of C than the traditional ratio of 0.58. Using these regressions for forest soils in the Rocky Mountains could be beneficial when estimating global or regional C pools.

Many studies estimate global soil organic matter ranging from 1000 to 3000 Pg C (Bolin et al., 1979; Bouwman and Leemans, 1995; Eswaran et al., 1993; Post et al., 1982, 1990). This study of Rocky Mountain forest soils has shown that depending on the conversion ratios used, these types of estimates could vary an additional ±42%. Additionally, we included components that are often ignored when estimating C (brown cubical rotten wood, soil wood, surface humus, and litter; Zinke et al., 1984). These components can often be major contributors to C storage in forest soils.

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