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CARBON AND NITROGEN IN THE LIGHT FRACTION OF A FOREST SOIL: VERTICAL DISTRIBUTION AND SEASONAL PATTERNS[1]

GODY SPYCHER, PHILLIP SOLLINS, AND SHARON ROSE

Department of Forest Science, Oregon State University, Corvallis, Oregon 97331

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ABSTRACT

We extracted light-fraction material densimetrically in NaI solution (specific gravity 1.65 g/cm^3) from root-free soil samples from a forested site in the Oregon Cascade Mountains. We chose extraction at this density because it excluded most of the organomineral particles from the light fraction. Major components identifiable from scanning electron micrographs were dead root fragments, hyphae, charcoal, and pumice—all with adsorbed or entrapped colloidal particles. Total soil carbon (C) and nitrogen (N) at the site averaged 145 and 7.4 megagrams per hectare, respectively, to a depth of 83 centimeters. Light-fraction material accounted for 53 percent of the total C and 45 percent of the total N in the 0- to 3-cm layer; these proportions decreased abruptly in the next layer and then more gradually over the remainder of the 83-cm profile. Amounts of light-fraction material increased by 50 to 100 percent from early spring to summer and then peaked again in the fall. This large seasonal fluctuation indicates that the light fraction provides an important labile reservoir of C and nutrient elements in the forest ecosystem.

INTRODUCTION

Soil organic matter is a vital pool of biogenic elements and energy in forest ecosystems (Gessel et al. 1973; Jenny 1980; Sollins et al. 1980). It has been studied most intensively in cultivated and grassland soils, where models have progressed from active/passive subdivision of soil organic matter (Jansson 1958) to compartmentalization in which living biomass, various forms of fresh detritus, and two or more phases of stabilized organic matter form the basic pools (Jenkinson and Rayner 1977; Paul and Van Veen 1978). Nutrient stores can also be partitioned into these same pools, although this has been done in only a few models of nutrient cycles (e.g., Smith 1979).

The half-life of stabilized organic substances is decades to millenia (Jenkinson and Rayner 1977). They are metabolized slowly because stabilization yields humified compounds whose decomposition requires numerous enzymes (Swaby and Ladd 1962) and because stabilized forms are adsorbed on mineral grains and occluded within aggregate structures, which may prevent or delay access by roots and microorganisms (Rovira and Greacen 1957). Fresh detritus accumulates mainly as separate, nonmineral particles; its turnover, which requires months to years, is regulated mainly by its chemical composition (e.g., Waid 1974; Staaf 1980).

Fresh detritus can be separated from stabilized organic matter by density fractionation. Methods vary widely; both organic (Henin and Turc 1950; Greenland and Ford 1964; Scheffer 1977) and inorganic media (Malone and Swartout 1969) have been used. Organic media (CCl_4, $C_2H_2Br_4$) permit extraction over a broader range of densities than inorganic media (NaI, $ZnBr_2$, CsCl), but require special precautions because of their toxicity. Surfactants are sometimes used to keep colloidal particles in suspension and to maximize yields (Ford and Greenland 1969), but they are adsorbed by both light and heavy particles (Francis 1973), which may interfere with subsequent measurements. Young and Spycher (1979) have found that surfactants can be eliminated without significant loss of precision if samples are extracted several times.

The light fraction was defined originally by Greenland and Ford (1964) as material lighter than 2.0 g/cm^3. More recently, a lower density (1.59 g/cm^3) has been used to exclude more organomineral and mineral material from the

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light fraction (Scheffer 1977; Ladd et al. 1977). In this paper, we describe the use of NaI solution (sp gr 1.65 g/cm^3) to remove the light fraction from soils and report results obtained by sampling over an entire year at a forested site in the Oregon Cascade Mountains.

STUDY SITE

The site occupies a glacial terrace at 610-m elevation on the McKenzie Ranger District, Willamette National Forest, about 7 km NW of the town of McKenzie Bridge, Oregon. Vegetation consists of a 70-yr-old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stand established naturally after fire; this stand was one of three selected by Santantonio (1979) to study biomass and turnover of fine roots. The site faces south; slope is about 10%. Annual rainfall in the area averages about 180 cm and mean annual temperature, about 8°C (Sollins et al. 1980). The site is drier than average for this region, as evidenced by its *Castanopsis chrysophylla* [Dougl. (A. DC.)] understory type (Franklin and Dyrness 1973).

The litter layer, a duff-mull about 5 cm thick, averages 29 Mg/ha (dry weight) excluding material >3 cm in diameter (D. Santantonio, personal communication). Soil is a typic dystrochrept developed in place from andesitic tuffs and breccias (Swanson and James 1975). There is little evidence of colluvial activity at the site. Upheaval accompanying tree fall appears to be the dominant soil-mixing process.

SOIL-SAMPLING PROCEDURES

Two sets of samples were gathered. The first set was collected monthly between March 1978 and February 1979 by D. Santantonio. An 18- by 24-m plot was established at the site and divided into nine subplots, each 6 × 8 m (Santantonio 1979). To determine sampling points within each subplot, 12 equally spaced grid points were laid out and numbered randomly. One soil core, 5 cm in diameter and up to 100 cm deep, was taken monthly at grid point no. 1 in each subplot for the first 3 mo, at grid point no. 2 in each subplot for the next 3 mo, and so on. Santantonio separated each core into 5-cm layers for his studies; we used the upper four layers for ours.

In April 1979, we gathered a second set of soil samples from four soil pits excavated about 10 m from the corners of the 18- × 24-m plot. At each pit, the profile was divided into a top layer (0 to 3 cm) and eight deeper layers, each 10 cm thick.

SEPARATIONS AND ANALYSES

Samples were air-dried, and all recognizable live and dead roots not passing a 0.85-mm sieve were removed. Lithic fragments larger than 2 mm were removed by sieving, and the soil was then ground to pass through a 60-mesh sieve. The separation medium was prepared by dissolving reagent-grade NaI in distilled water and adjusting the density to 1.65 g/cm^3 with a hydrometer. Our choice of this density was based on earlier studies in which fresh detrital material was separated from organomineral and mineral particles (Satoh and Yamane 1972; Scheffer 1977; Ladd and Amato 1980).

Five grams of ground soil was suspended in 25 ml of NaI solution and dispersed by stirring rapidly at about 1800 rpm for 30 s. Suspensions were immediately centrifuged in a swinging bucket rotor at 5000 *g*. The supernatant solution with floating particles (the light fraction) was decanted onto polycarbonate filters (5-μm pores); particles were then washed with 200 ml of distilled water, dried for 16 h at 70°C, and weighed. The heavy residue was reextracted twice at the same density or until amounts of supernatant particles became negligible, washed three times in distilled water, and dried at 70°C. An aliquot of the light-fraction material was heated to 550°C for 4 h and is hereafter referred to as the *ash subfraction*.

Whole soil and the heavy-fraction residue were analyzed for carbon (C) and nitrogen (N). Lithic fragments (2 to 50 mm) were ground and also analyzed for C. Carbon was determined by combustion in an induction furnace (Leco WR 12 Automatic Carbon Analyzer), N by micro-Kjeldahl (digestion temperature of about 320°C). Light-fraction material was not analyzed for C and N; instead, light-fraction C and N, as percentages of whole soil, were computed from the concentrations in whole soil and heavy residue.

Oven-dried or freeze-dried light-fraction components and identifiable particles handpicked from unground soil samples were mounted on aluminum stubs, coated with gold-palladium alloy, and examined with an AMR 1200 scanning electron microscope.

RESULTS

Electron micrographs of light-fraction particles

The micrographs illustrate major light-fraction components, including mineral particles (Fig. 1). Many of the light-fraction particles appearing in the more than 100 micrographs we processed could not be identified unequivocally except for woody particles or mineral fragments that were identified and handpicked before examination with the electron microscope. In random samples of light-fraction particles, organic surfaces could be distinguished from mineral surfaces only when remnant tissue or characteristic mineral structures were present.

Fungal and actinomycete hyphae were the only recognizable microbial structures. Some appeared as collapsed bands (Figs. 1c and 1f), but others retained their tubular shape (Figs. 1b and 1d), apparently due to a coating of partially dissolved calcium oxalate crystals on the hyphae (Graustein et al. 1977). Organic detritus included plant fragments (Figs. 1a and 1c), roots (Fig. 1b), and charcoal (Fig. 1d). These particles were frequently encrusted with colloidal soil particles

FIG. 1a. Mixture of hyphae and mineral and organic particles ranging in size from 20 to 200 μm (15-cm depth).

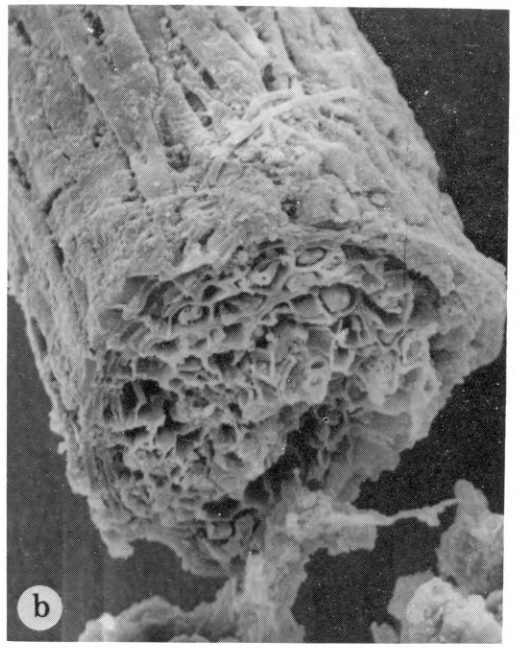

FIG. 1b. Decomposing root fragment, ~90 μm in diameter. Surface encrusted with colloidal particles and intergrown with hyphae. Ultrasonic cleaning (3 min at 150 W) following extraction failed to remove incrustation (75-cm depth).

(Figs. 1b and 1d) that were not removed effectively by ultrasonic treatment. Continuous crusts appear to have been present before fractionation (Figs. 1b and 1d), although some of the crust material may have accumulated as a result of adsorption and entrapment of clay-size particles during fractionation (Figs. 1b, 1d, and 1e).

Translucent, brittle pumice particles were the dominant mineral component in the light fraction. Most of them were nearly white, indicating low content of adsorbed organic matter. They were highly vesicular and tended to entrap clay-size soil particles (Fig. 1e). Weathered feldspar (Berner and Holdren 1977) and some light aggregate structures (Fig. 1f) were among other mineral components that appeared in the light fraction.

Amounts and distributions of C *and* N

Means and standard deviations of properties measured in samples from the four soil pits are shown in Table 1. We calculated that total soil C and N at the site averaged 145 Mg/ha (metric

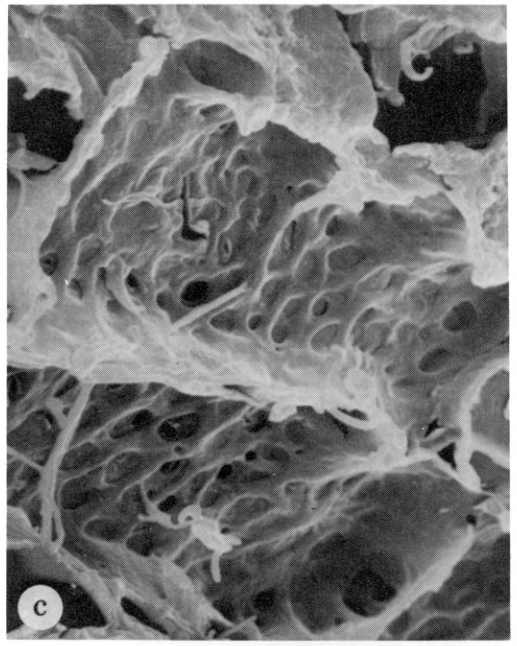

FIG. 1c. Fragment of conducting vessel, ~10 μm wide. Globules are most likely clay particles (amorphous) either adsorbed during fractionation or originally present as crusts (5-cm depth).

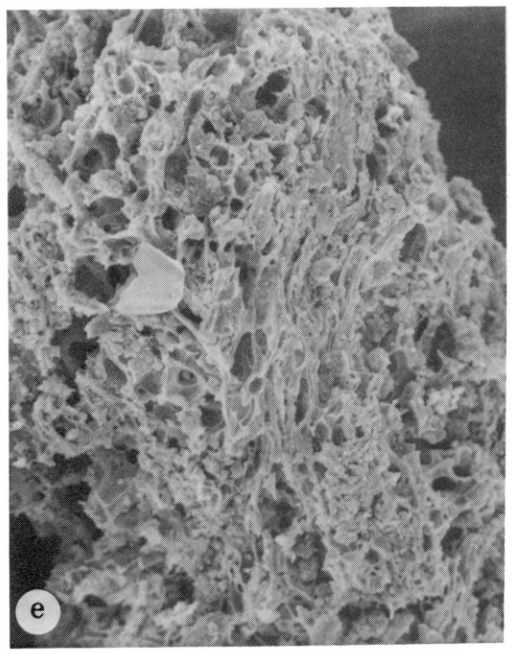

FIG. 1e. Fungi and actinomycetes (?) growing on handpicked woody fragment. Numerous soil particles 1 μm and larger remain on surface (5-cm depth).

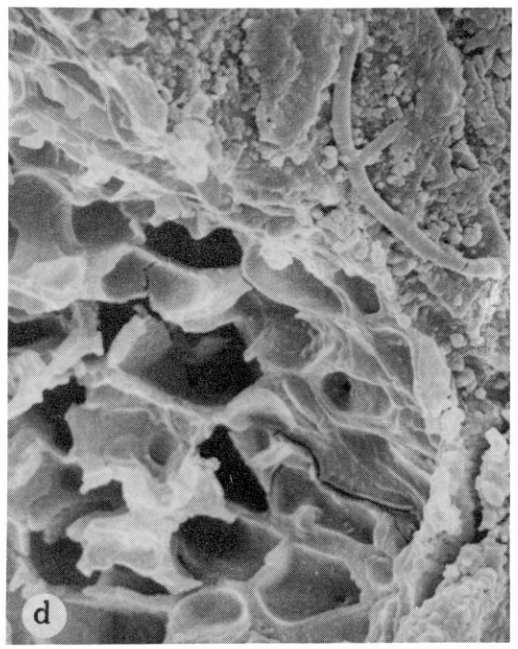

FIG. 1d. Tissue fragment with hyphae (5-cm depth).

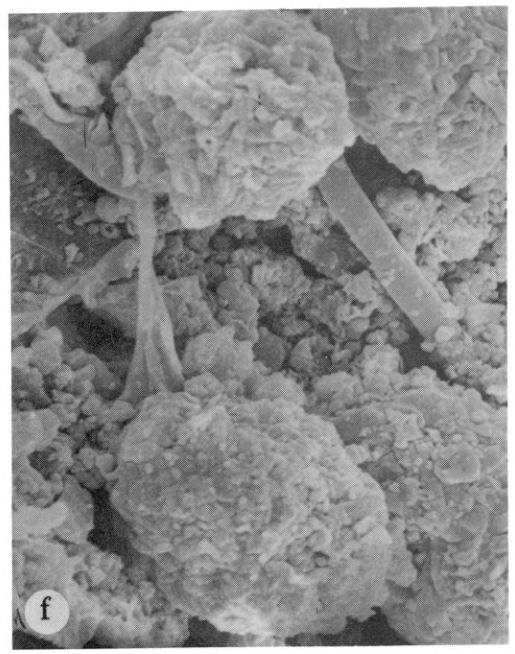

FIG. 1f. Surface of woody fragment. Protuberances on hyphal fragments may be remnants of calcium oxalate crystals (Graustein et al. 1977) (5-cm depth).

tonne/ha) and 7.4 Mg/ha (Table 2, Fig. 2). Coarse lithic fragments (2–50 mm) occupied 5 to 9% of the soil volume and accounted for about 8 Mg/ha of C, or 5.6% of the total soil C. Most of this organic matter was adsorbed on surfaces and occluded within concretions.

In the 0- to 3-cm layer, the light fraction accounted for 53% of the total C and 45% of the total N (Table 2). These proportions decreased abruptly in the next layer and then more gradually over the remainder of the 83-cm profile.

The C/N ratio of whole soil decreased from 25.8 in the surface layer to 15.6 in the 63- to 83-cm layer; similarly, the C/N ratio of the heavy fraction decreased from 21.9 to 12.9 (Table 2). However, the C/N ratio of the light fraction was much wider and more variable with depth, principally because of charcoal particles irregularly distributed with depth and the large impact of analytical errors at very low N concentrations on calculated C/N ratios.

Not all the C and N in the light fraction is in recent detritus. The electron micrographs indicate that the ash subfraction contained some adsorbed organic matter in the form of organomineral particles. However, the amount of

TABLE 1

Mean values (and standard deviations) for measured properties in soil samples from four profiles

Depth, cm	Bulk density, g/cm³	C		N		Light fraction, dry wt	Ash subfraction, % of light fraction
		Whole soil	Heavy fraction	Whole soil	Heavy fraction		
		% of whole soil					
0–3	0.46	11.67	5.35	0.456	0.246	18.1	35.8
	(0.03)	(2.37)	(0.82)	(0.050)	(0.028)	(3.6)	(1.0)
3–13	0.67	5.29	3.43	0.233	0.199	4.8	45.8
	(0.03)	(0.47)	(0.61)	(0.033)	(0.027)	(0.3)	(6.5)
13–23	0.71	3.01	1.97	0.176	0.150	2.6	44.0
	(0.04)	(0.35)	(0.22)	(0.028)	(0.021)	(0.3)	(3.2)
23–43	0.66	2.46	1.69	0.137	0.117	2.4	49.0
	(0.03)	(0.31)	(0.21)	(0.009)	(0.007)	(0.2)	(4.6)
43–63	0.65	1.75	1.29	0.107	0.101	1.8	60.8
	(0.04)	(0.06)	(0.04)	(0.008)	(0.009)	(0.2)	(3.2)
63–83	0.65	1.53	1.16	0.098	0.090	1.7	58.5
	(0.01)	(0.12)	(0.06)	(0.009)	(0.006)	(0.3)	(2.5)

TABLE 2

Mean values (and standard deviations) for soil properties, calculated from data presented in Table 1[a]

Depth, cm	Ash-free LF, % of whole soil	C in LF, % of total C	N in LF, % of total N	% C in ash-free LF	% N in ash-free LF	C/N			C		N	
						Whole soil	Heavy fraction	LF	Whole soil	LF	Whole soil	LF
									Mg/ha			
0–3	11.6	53	45	53	1.81	25.8	21.9	30.8	15.7	8.3	0.60	0.27
	(2.3)	(9)	(10)	(8)	(0.43)	(5.5)	(3.8)	(8.5)	(3.5)	(3.1)	(0.06)	(0.09)
3–13	2.6	36	15	73	1.32	22.7	17.3	56.8	34.3	11.3	1.41	0.21
	(0.1)	(8)	(2)	(11)	(0.20)	(3.1)	(2.4)	(16.5)	(4.6)	(1.4)	(0.30)	(0.05)
13–23	1.5	34	15	72	1.81	17.1	13.2	40.8	21.3	6.8	1.16	0.17
	(0.2)	(6)	(4)	(11)	(0.43)	(0.8)	(1.1)	(5.7)	(2.2)	(1.5)	(0.18)	(0.05)
23–43	1.2	30	15	56	1.62	17.7	14.4	40.5	32.1	9.0	1.69	0.25
	(0.1)	(5)	(4)	(13)	(0.41)	(1.8)	(1.1)	(19.9)	(2.7)	(1.9)	(0.11)	(0.08)
43–63	0.7	27	7	67	1.00	16.3	12.8	70.7	22.7	5.7	1.32	0.08
	(0.1)	(2)	(2)	(12)	(0.37)	(1.8)	(0.9)	(16.2)	(1.2)	(0.5)	(0.15)	(0.02)
63–83	0.7	24	8	53	1.17	15.6	12.9	49.6	19.3	4.4	1.19	0.09
	(0.1)	(2)	(2)	(7)	(0.44)	(0.9)	(0.7)	(17.8)	(1.0)	(0.6)	(0.09)	(0.04)
Mean	3.1	34.0	17.5	62	1.46	19.2	15.4	48.2				
0–83 sum									145.4	45.5	7.37	1.07

[a] LF is light fraction.

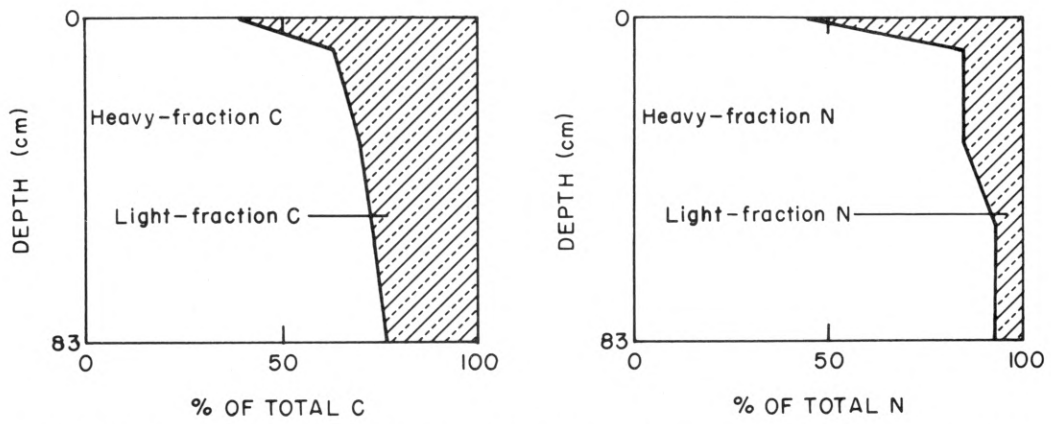

FIG. 2. Distribution of total C and N between light and heavy fractions over an 83-cm forest-soil profile. Mean of four profiles. Heavy-fraction C, 99.9 Mg/ha; light-fraction C, 45.5 Mg/ha. Heavy-fraction N, 6.27 Mg/ha; light-fraction N, 1.07 Mg/ha.

TABLE 3

Concentration of light-fraction material extracted from root-free soil; means and standard errors for nine cores each month

Month	Light fraction, % of whole soil							
	0–5 cm		5–10 cm		10–15 cm		15–20 cm	
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
March 1978	47.3	9.6	11.8	1.9	4.8	0.9	3.5	0.7
April	62.7	7.1	12.3	1.8	5.9	0.7	3.5	0.4
May	73.6	6.6	14.3	1.2	5.3	0.4	4.3	0.6
June	88.4	7.0	18.8	3.1	7.4	0.4	–	–
July	57.7	6.4	15.2	1.5	8.4	0.9	6.5	0.6
August	68.7	8.2	12.4	0.9	8.0	0.9	6.0	0.9
September	32.8	4.4	12.5	0.8	9.1	0.6	7.4	0.4
October	43.5	2.6	15.5	1.5	8.7	0.7	6.7	0.9
November	45.9	6.0	15.4	2.7	6.0	1.0	2.5	0.5
December	45.6	5.4	11.0	0.4	5.7	0.8	4.1	0.8
January 1979	31.8	2.7	11.9	0.8	6.6	0.8	5.6	1.0
February	44.2	5.6	15.8	3.3	6.4	1.2	3.2	0.5

ash-associated C and N is difficult to estimate reliably.

Seasonal variation

Amounts of light-fraction material in cores collected monthly in early spring 1978 (Table 3) were similar to those in samples collected from soil pits in spring 1979 (Table 2), except in the topmost 5-cm layer. In that layer, the 1978 cores yielded about three times as much light-fraction material, probably because more of the humus layer was included in the first set of samples than in the second. Concentrations peaked in June in the uppermost two layers, declined during late summer, and increased again slightly in the late fall. This type of fluctuation is probably related to the precipitation and temperature patterns of the area; a similar fluctuation has been observed at other Douglas-fir sites for fungal biomass (Fogel and Hunt 1979) and soil solution chemistry (Sollins and McCorison 1981). In the lowest two layers, concentrations of light-fraction material gradually increased through spring and peaked in late summer. Differences between March and peak levels were significant ($p < 0.05$ by two-tailed t test) in all layers except the second ($p < 0.10$).

In each of the three lowest layers, a 1% increase in concentration of light fraction corresponds to ~2 Mg/ha increase in amount of light fraction. In the 5- to 10-cm layer, light-fraction concentration increased by 7% from April to June, or about 14 Mg/ha. Because we have no reason to expect that amounts of ash-associated C in the light fraction vary within the year, the changes in amounts of light-fraction material should constitute net changes in the amounts of fresh detritus and microbial biomass.

DISCUSSION

The choice of density for particle fractionation depends on the study objectives and soil properties under consideration. A study of Oregon soils representing six soil orders showed that most clay-size organomineral particles were lighter than 2.0 g/cm^3 except in an iron-rich ultisol (Young and Spycher 1979; Spycher and Young 1979). At our McKenzie Bridge site, organomineral particles in the heavy-fraction residue ranged from 1.80 to 2.1 g/cm^3 for clay-size particles and from 1.8 to >2.3 for silt-size particles (G. Spycher, unpublished data). We chose extraction at 1.65 g/cm^3 because this seemed to exclude most of the organomineral particles from the light fraction except those bound in microcrusts on organic detritus or trapped in porous mineral particles and aggregates. It must be recognized, however, that such mineral inclusions can contribute significant amounts of C to the light fraction, particularly in soils containing high concentrations of strongly aggregating amorphous mineral oxides (El-Swaify and Emerson 1975).

In several grassland and cultivated soils, Greenland and Ford (1964) found that the light fraction accounted for up to 48% of total soil C and up to 32% of N. Our results are quite similar to theirs, even though they extracted light fraction at 2.0 g/cm^3; many of their soils were ultisols and presumably contained little organomineral material between 1.65 and 2.0 g/cm^3. Ash contents of their light fractions and ours were similar, but phytoliths rather than pumice particles were the dominant mineral component in theirs.

Despite complications arising from admixture of charcoal and mineral particles in the light fraction, the light and heavy fractions clearly constitute two distinct pools of organic matter at our site, especially below the top 3 cm. The heavy fraction is C-deficient (C/N < 17), whereas the light fraction is N-deficient (C/N > 40). [For many substrates, a C/N ratio of 20 to 30 defines approximately the boundary between C and N deficiency (e.g., Parnas 1976)].

Ford and Greenland (1968) suggested that organic N is mineralized more rapidly from a light fraction extracted at 2.06 g/cm^3 than from the residual heavy fraction. Ladd and Amato (1980) were unable to observe significant differences in N mineralization between light- and heavy- (2.06 g/cm^3) particle fractions and suggested that such a difference is more likely to be observable if the light fraction is extracted at a lower density (e.g., 1.6 g/cm^3). Because all their results refer to cultivated soils and were restricted to the surface horizon, care is required when comparing their results with ours.

At our site, the light fraction accounted for a larger proportion of C and N near the surface than in deeper layers (Fig. 2). At the surface, detrital inputs are large (mostly dead roots mixed, perhaps, with litter), and the light fraction accounts for a correspondingly large proportion of the total C and N. The proportion represented by heavy (presumably adsorbed) fraction increases deeper in the profile, suggesting that detrital inputs are less important and that percolation of dissolved organics downward is more important. Well below the rooting zone (e.g., at the 2.0-m depth at our study site), we would expect detrital inputs to be negligible, virtually all the organic matter to have percolated in solution from above, and the adsorbed phase to account for a very large proportion of total soil C and N.

The increase in light-fraction material from March to June at the 5- to 15-cm depth was about 38 Mg/ha, about 20 Mg/ha of it ash-free. Turnover of live roots in these same cores (over the entire 1-m profile) was considerably less, 12 Mg/ha annually (Santantonio 1979). At a young Douglas-fir stand in the Oregon Coast Range, Fogel and Hunt (1979) calculated fine-root turnover (excluding mycorrhizal tissues) of 9 Mg ha^{-1} yr^{-1}, mycorrhizal-tissue turnover of 8 Mg ha^{-1} yr^{-1}, and soil-hyphae turnover of 7 Mg ha^{-1} yr^{-1}. Consequently, turnover of roots and fungal tissues together could produce the increases we observed in amounts of light-fraction material, but it seems likely that at least some material was transferred from adsorbed heavy-fraction organic matter to the light fraction as a result of microbial activity. Regardless, light-fraction organic matter, together with organic matter ad-

sorbed on accessible aggregate surfaces, provides an important reservoir of rapidly cycling C and nutrient elements in the forest ecosystem.

ACKNOWLEDGMENTS

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