

Sulfur fractions and retention mechanisms in forest soils

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The relevance of organosulfur formation and sulfate adsorption as S retention mechanisms in forest soils based upon the sulfur status of samples collected by horizon was investigated. Several forests of varying elevation, vegetation, location, and soil type were considered. Organic S was found to constitute over 78% of total S in the uppermost mineral (0-20 cm; A,E) horizons. This trend was also observed for both intermediate (20-40 cm; primarily A/B) and deeper (40+ cm; B,C) horizons, where organic S exceeded 65% of total S in all but one site examined. Adsorbed sulfate generally constituted only a minor component of the S pool in the uppermost mineral horizons (<13% of total S in all sites examined). This trend was also observed with increasing depth, although in the lowermost horizons adsorbed sulfate increased on a percentage basis. In almost all cases, the adsorbed anion constituted substantially less of the total S than did organic S, irrespective of depth. Carbon-bonded S was the most prevalent form of organic S for most sites at all depths examined. Adsorbed ester sulfate, recovered by extraction with basic phosphate, generally constituted a substantial portion of the adsorbed S pool for both O1 and O2 components of the forest floor and for the uppermost mineral horizon of most sites examined. This trend did not hold true with increasing depth. Because organic S was the dominant form of S, irrespective of horizon, the data suggest that organosulfur formation, not sulfate adsorption, may represent the primary mechanism for S retention in forest soil.

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La pertinence de la formation de composés organiques soufrés et de l'adsorption des sulfates comme mécanismes de rétention du soufre dans les sols forestiers a été étudiée sur des échantillons récoltés par horizon. Plusieurs forêts variant quant à l'altitude, la végétation, la localisation et le type de sol ont été considérées. La fraction soufrée organique correspond à plus de 78% du S total dans les horizons minéraux de surface (0-20 cm : A, E). Ce patron a aussi été observé pour les horizons intermédiaires (20-40 cm; principalement A/B) et les horizons en profondeur (40+ cm; B, C), où le S organique a excédé 65% du S total dans toutes les stations étudiées à l'exception d'une. Le sulfate adsorbé a constitué généralement seulement une composante mineure du pool de S dans les horizons minéraux de surface (<13% du S total dans toutes les stations étudiées). Ce patron a aussi été observé dans les horizons plus profonds bien que dans le dernier horizon, le sulfate adsorbé représente un pourcentage plus élevé du S total. Dans presque tous les cas, l'anion adsorbé comprend substantiellement moins de S total comparé à S organique, indépendamment de la profondeur. Le S lié au carbone était la forme organique prédominante de S pour la majorité des stations et ce, pour toutes les profondeurs examinées. L'ester de sulfate adsorbé, extrait au phosphate basique, comprend généralement une portion substantielle du pool du S adsorbé pour les horizons O1 et O2 de la couverture morte et pour l'horizon minéral de surface pour la majorité des stations examinées. Ce patron ne s'applique toutefois pas aux horizons plus en profondeur. Étant donné que le S organique était la forme dominante de S, quelque soit l'horizon, les données suggèrent que la formation de composés organiques soufrés et non d'adsorption des sulfates, peut représenter le mécanisme premier pour la rétention de S dans les sols forestiers.

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Introduction

Sulfur accumulation from acidic precipitation has been documented for forested ecosystems in the southeastern, northwestern, and northeastern United States (Cole and Johnson 1977; Swank and Douglass 1977; Henderson et al. 1977; Johnson et al. 1982). Two principal mechanisms by which this can occur are sulfate adsorption (Johnson and Henderson 1979; Johnson et al. 1979, 1982) or by the microbial incorporation of sulfate S into organic matter (Fitzgerald et al. 1983, 1985; Watwood et al. 1988). It should be noted that other sources of soil S, litter and foliage, also contain organic S, comprising chiefly amino acid and sulfolipid S (Anderson 1975; Harwood and Nicholls 1979). These forms of S can accumulate in the upper horizons and then translocated to the lower ones by percolating water (Schoenau and Bettany 1987). However, this organic S of plant origin is mineralized rapidly to sulfate (Strickland and Fitzgerald 1983; Fitzgerald et al. 1988a), and is therefore

subject to the same possible fates as atmospherically derived sulfate.

The bulk of the work on S retention in forested ecosystems has concentrated mainly on processes occurring in the forest floor (O1 and O2 horizons) and uppermost mineral soil horizon. The contribution of organosulfur formation processes to S retention in these horizons has been investigated extensively (Strickland et al. 1986, 1987; Watwood et al. 1986; Fitzgerald et al. 1988b; Watwood et al. 1988). However, the intermediate and lowermost soil horizons have been given only cursory attention. In the limited work that has been carried out on depth profiles, Swank et al. (1984) found that organic S formation potentials decreased with increasing depth, but when quantities of substrate representative of each horizon were considered, substantial rates were apparent, even with samples collected from the Bw (26-65 cm) horizon of a hardwood forest in North Carolina. Based upon a detailed analysis of sulfate flux, Cole and Johnson (1977) suggested that adsorption plays a more important role in retention in lower horizons

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TABLE 1. Forested study sites investigated

Site	Symbol	Location	Vegetation	Soils	Elevation (m)
Florida	FS	Gainesville, FL	Slash pine	Spodosols	0
Douglas-fir	DF	Thompson Forest, WA	Douglas-fir	Inceptisols	100
Red alder	RA	Thompson Forest, WA	Red alder (mature)	Inceptisols	100
B. F. Grant Forest	GL	Eatonton, GA	Loblolly pine	Ultisols	175
Norway spruce	NS	Nordmonen, Norway	Norway spruce	Entisols	202
Duke Forest	DL	Mebane, NC	Loblolly pine	Ultisols	215
Tarklin	TK	Walker Branch, TN	Mixed deciduous	Ultisols	300
Fullerton	FT	Walker Branch, TN	Mixed deciduous	Ultisols	300
Loblolly pine	LP	Oakridge, TN	Loblolly pine	Ultisols	300
Turkey Lakes	TL	Ontario, Canada	Sugar maple - birch	Spodosols	350
Camp branch	CB	Falls Creek, TN	Mixed oak	Ultisols	550
Mixed deciduous	CH	Coweeta, NC	Oak-hickory	Ultisols	700-1000
White pine	CP	Coweeta, NC	White pine	Ultisols	800-1100
Whiteface Mtn.	WF	Lake Placid, NY	Spruce-fir	Histosols, Spodosols	1000-1500
Findley Lake	FL	Findley Lake, WA	Fir-hemlock	Inceptisols	1800
Becking	SS	Great Smokey Mtns., NC	Red spruce, beech	Inceptisols	1800
Indian Gap	SB	Great Smokey Mtns., NC	Red spruce, beech	Inceptisols	1800
Nolan Divide	ST	Great Smokey Mtns., NC	Red spruce, beech	Inceptisols	1800

than does organic S formation. Moreover, Johnson et al. (1982) further suggested that over 80% of the S accumulation at Walker Branch Watershed in Tennessee was accomplished via sulfate adsorption to subsurface soils.

The prevailing view, upon which some models for the sulfur cycle in forest soils have been based is that sulfate adsorption plays a major role in S retention, especially as depth increases (Mitchell and Fuller 1988). The existing data suggest otherwise. Thus, others found that organic S is a major component of the intermediate and lower soil horizons (David et al. 1982, 1983, 1987; Mitchell et al. 1986; Watwood et al. 1988), suggesting that organic S formation should be given more consideration as an S retention mechanism at all depths within these profiles. In light of this apparent contradiction, determination of both adsorbed as well as organic S pool sizes on the same samples for a variety of sites is warranted to better ascertain which mechanism plays the more important role when depth is considered.

Materials and methods

Site description and sampling

A partial description of the sites is provided in Table 1. Samples were collected from the two litter layers (O1 and O2) and where applicable, from the uppermost mineral soil horizon, intermediate mineral soil horizons, and the lowermost mineral soil horizon from excavated pits at each site. Samples from all horizons (both litter and mineral soil) were sieved (<1 cm), and all roots and stones were removed by hand. These samples were then maintained, field moist, at 4°C prior to analysis.

Intrinsic sulfur analysis

Intrinsic forms of S, those S-containing moieties endogenous to the soil, were quantified as follows. Total S was determined by hydriodic acid (HI) reduction after alkaline oxidation with sodium hypobromite (Tabatabai and Bremner 1970). Total HI-reducible S, consisting of ester sulfate and inorganic sulfate, was quantified by direct reduction with HI (Frenay 1961). Carbon-bonded S, consisting of amino acid S and probably sulfonate S, was calculated as the difference between total HI-reducible S and total S.

For determination of soluble and adsorbed S pool sizes, the following procedure was used. To generate the soluble fraction, a 1:5 soil-water mixture was shaken 15 min and centrifuged. The supernatant, containing soluble S, was then filtered (0.22- μ m membrane)

and stored at 4°C prior to analysis. To obtain adsorbed forms of S, the residue was resuspended and shaken for 30 min with 0.02 M Na_2HPO_4 (pH 7.9) in a 5:1 ratio. This procedure was repeated, and the resulting supernatants that were collected by centrifugation were pooled and filtered sequentially through 0.45- and 0.22- μ m membranes. The filtered extract, containing adsorbed forms of S, was stored at 4°C prior to analysis.

Soluble S was determined by HI reduction (Frenay 1961), whereas soluble inorganic sulfate was quantified by anion chromatography (Dick and Tabatabai 1979). Soluble ester sulfate was calculated as the difference between these two S pools. An identical treatment was used to quantify adsorbed ester sulfate and adsorbed inorganic sulfate. Insoluble ester sulfate, that which failed to be extracted by either water or Na_2HPO_4 , was calculated as the difference between total HI-reducible S and the sum of the soluble and the adsorbed HI-reducible S. Although inorganic non-sulfate S has been detected in forest soils (Wainwright 1979; David et al. 1983), these various forms constituted only a small percentage of total S and were not determined in the present study.

Results and discussion

In general, the pool size of adsorbed S, containing both ester-linked sulfate and inorganic sulfate, exceeded that of the analogous soluble pool. This was true for the O1 horizon at 8 out of 15 sites examined (Fig. 1). For example, the Douglas-fir, red alder, Coweeta white pine, and Coweeta mixed deciduous sites had adsorbed S pool sizes that were more than twice that of the analogous soluble pool. This trend was more pronounced in the O2 horizon, with 14 out of 16 sites showing substantial differences between adsorbed and soluble S pools (Fig. 2). The exceptions to this trend were the Turkey Lakes and camp branch sites, where O2 horizon soluble S pool sizes exceeded those of the adsorbed pool. Similar findings were made for O2 horizon samples taken from the Santa Fe National Forest in New Mexico (Watwood et al. 1986). This trend was also evident in the uppermost (0-20 cm; A,E) mineral soil horizons (Table 2) and most pronounced in the intermediate (20-40 cm; primarily A/B) and lowermost (40+ cm; primarily B,C) soil horizons (Tables 3 and 4), where all sites examined exhibited more adsorbed S than soluble S. This was not surprising since others (Johnson and Henderson

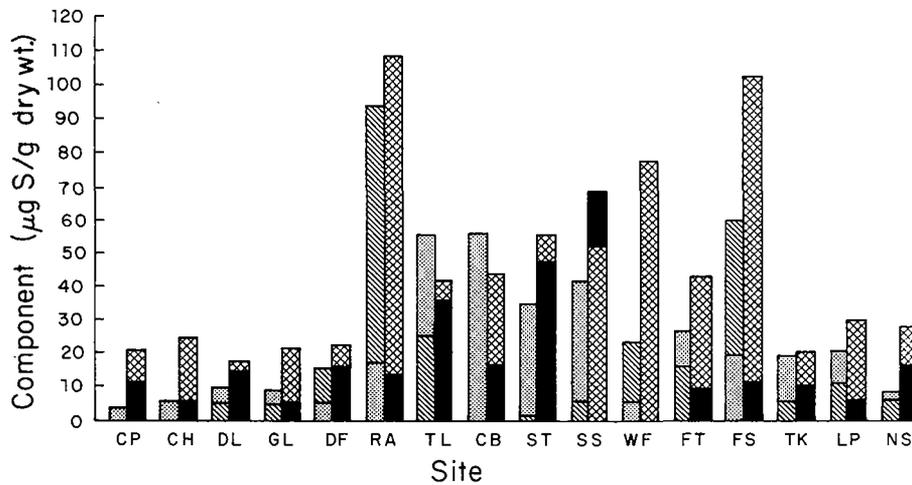


FIG. 1. Soluble and adsorbed sulfur components of O1 horizon samples collected in 1985 from various forested study sites. \square , soluble sulfate; ▨ , ester sulfate; \blacksquare , adsorbed sulfate; ▩ , ester sulfate. See Table 1 for explanation of site symbols.

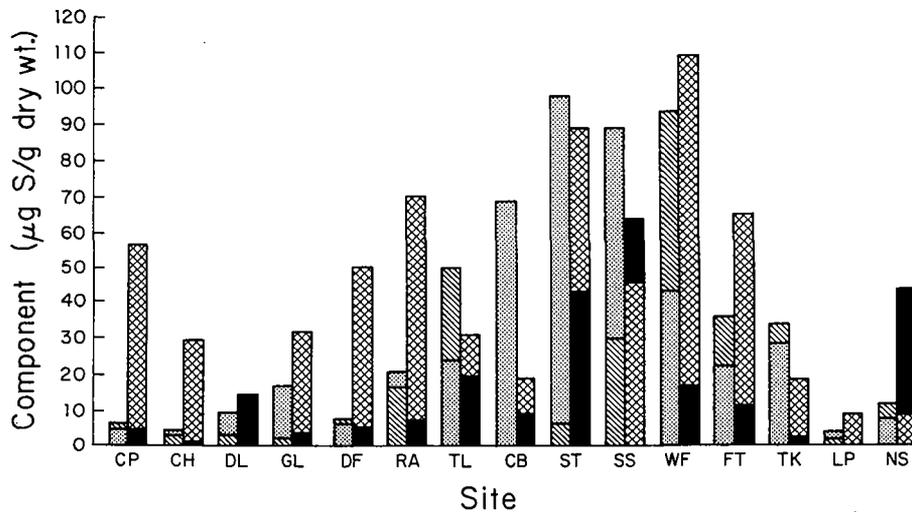


FIG. 2. Soluble and adsorbed sulfur components of O2 horizon samples collected in 1985 from various forested study sites. \square , soluble sulfate; ▨ , ester sulfate; \blacksquare , adsorbed sulfate; ▩ , ester sulfate. See Table 1 for explanation of site symbols.

1979; David et al. 1983) found that the adsorbed pool of S exceeded the water soluble pool in both intermediate and lowermost soil horizons. This trend with depth is in agreement with findings that adsorption is generally associated with iron and aluminum hydrous oxides and sesquioxides (Chao et al. 1964; Johnson and Cole 1980), and results of previous research at the Fullerton site (Peters et al. 1970) have shown that iron content does tend to increase with increasing depth.

Within the adsorbed S pool, S bound in an ester linkage was present in larger quantities than was inorganic sulfate in the O1 and O2 horizons at 13 out of 15 and 15 out of 16 sites examined, respectively (Figs. 1 and 2). For example, O1 litter from the Nolan Divide, Whiteface, Fullerton, and red alder sites possessed adsorbed ester S pool sizes of more than double those of the adsorbed sulfate pool. This trend was also apparent in the uppermost mineral soil horizon (Table 2), but was not so obvious for intermediate (20–40 cm; primarily A/B) soil horizons (Table 3) and occurred in only 6 out of 15 lowermost (40+ cm; primarily B,C) horizons examined (Table 4). Previous studies at Walker Branch, Tennessee (Johnson and Henderson 1979;

Johnson et al. 1981), Huntington Forest, New York (David et al. 1983), and Marmot Basin, Alberta (Mitchell et al. 1986), neglected to assay for adsorbed ester sulfate, although David et al. (1983) noted that the inorganic sulfate levels at Huntington Forest might be overestimated since this pool size was estimated by measuring total extractable HI reducible S. Based on the findings of the present study, we submit that adsorbed ester sulfate is an important fraction of organic S that should be quantified to fully assess the intrinsic S status of forest soil and litter. While ester sulfate levels usually exceeded inorganic sulfate levels in the adsorbed S pool, the same could not be said for the soluble S pool. In the O1 horizon, soluble ester S levels exceeded those of soluble sulfate at only 7 out of 16 sites examined (Fig. 1), and in the O2 horizon, this was observed only with samples collected from the Douglas-fir, red alder, Whiteface, and Florida sites (Fig. 2).

In most mineral horizons, organic S was the largest S-containing constituent. In the uppermost horizon, organic S accounted for greater than 78% of total S in all 25 horizons studied (Table 2). This was also true of the intermediate and lowermost soil horizons (Tables 3 and 4),

TABLE 2. Intrinsic sulfur status of uppermost (0–20 cm) mineral soil horizons of various forested study sites

Site; horizon	Year sampled	Total sulfur	Total organic sulfur	Carbon-bonded sulfur	Adsorbed ester sulfate	Soluble ester sulfate	Adsorbed sulfate	Soluble sulfate
White pine; A	1985	150	138 (92.0)	49.2 (32.8)	nd	1.5 (1.0)	9.7 (6.4)	2.4 (1.6)
Mixed deciduous; A	1985	226	210 (92.6)	145 (63.9)	nd	nd	7.7 (3.4)	9.0 (4.0)
Duke Forest; A	1985	67.1	59.1 (88.1)	25.1 (37.4)	19.7 (29.4)	4.4 (6.6)	5.5 (8.2)	2.5 (3.7)
B. F. Grant Forest; A	1985	151	127 (87.0)	103 (70.7)	8.1 (5.6)	4.6 (3.1)	5.6 (3.9)	13.1 (9.0)
B. F. Grant Forest; A	1988	108	84.2 (78.0)	12.2 (11.2)	22.4 (20.7)	2.7 (2.5)	15.0 (13.9)	8.8 (8.2)
Findley Lake; A2	1985	1725	1710 (99.3)	1190 (68.8)	5.1 (0.3)	430 (24.9)	2.7 (0.2)	9.1 (0.5)
Douglas-fir; A	1985	355	339 (95.5)	283 (79.5)	53.5 (15.1)	3.3 (0.9)	8.2 (2.3)	7.8 (2.2)
Red alder; A	1985	987	979 (99.1)	746 (75.6)	109 (11.0)	124 (12.5)	5.9 (0.6)	2.5 (0.3)
Turkey Lakes; A	1985	1260	1230 (97.4)	1030 (81.3)	26.6 (2.1)	16.1 (1.3)	7.7 (0.6)	25.7 (2.0)
Camp branch; A	1985	171	151 (88.3)	99.7 (58.2)	39.6 (23.1)	nd	4.3 (2.5)	15.9 (9.3)
Nolan Divide; A	1985	631	595 (94.2)	272 (43.0)	40.5 (6.4)	nd	28.2 (4.5)	8.1 (1.3)
Nolan Divide; A	1986	485	474 (97.7)	103 (21.2)	44.6 (9.2)	26.9 (5.6)	6.5 (1.4)	4.7 (0.9)
Becking; A	1985	236	205 (86.8)	78.8 (33.5)	84.1 (35.7)	10.2 (4.3)	20.6 (8.7)	10.6 (4.4)
Becking; A	1986	607	578 (95.2)	308 (50.9)	51.8 (8.5)	9.8 (1.6)	23.9 (3.9)	5.5 (0.9)
Whiteface Mtn.; A	1985	219	219 (100)	146 (66.7)	18.6 (8.5)	9.3 (4.2)	nd	nd
Whiteface Mtn.; A	1987	603	557 (92.3)	364 (60.3)	15.7 (2.6)	17.4 (2.9)	33.6 (5.6)	12.7 (2.1)
Fullerton; A	1985	250	230 (92.2)	148 (59.2)	8.7 (3.5)	nd	4.9 (1.9)	14.7 (5.9)
Fullerton; Ap	1986	480	449 (93.7)	381 (79.4)	30.7 (6.4)	15.8 (3.3)	18.2 (3.8)	12.3 (2.6)
Tarklin; A	1985	612	602 (98.3)	490 (80.1)	4.0 (0.7)	nd	1.7 (0.3)	8.8 (1.4)
Tarklin; A1	1986	247	218 (88.2)	112 (45.5)	16.3 (6.6)	5.4 (2.2)	19.3 (7.8)	9.8 (4.0)
Loblolly pine; Ap	1985	374	368 (98.6)	263 (70.2)	3.1 (0.8)	nd	2.4 (0.6)	2.9 (0.8)
Loblolly pine; A	1986	178	167 (93.8)	106 (59.6)	51.5 (29.0)	8.5 (4.8)	7.5 (4.2)	3.7 (2.0)
Norway spruce; E	1987	216	194 (89.5)	159 (73.5)	nd	nd	15.6 (7.2)	7.2 (3.3)
Indian Gap; A	1985	492	464 (94.2)	215 (43.6)	44.4 (9.0)	39.3 (8.0)	21.6 (4.4)	6.9 (1.4)
Indian Gap; A	1986	529	505 (95.4)	121 (22.9)	92.0 (17.4)	15.7 (3.0)	15.3 (2.9)	9.0 (1.6)

NOTE: Results are expressed as means of μg sulfur/g dry wt. with $n = 3$. SE < 15% in all cases. Values in parentheses represent the percentage of total sulfur. nd, not detected.

with the B. F. Grant Forest site being the only exception. Albeit there was more variability associated with organic S as a percentage of total S in the lower horizons, adsorbed sulfate nevertheless was a major S constituent (78% of total S) in the Bt horizon of this site. These results are similar to those of David et al. (1983, 1987) and Mitchell et al. (1986) who found that irrespective of depth, organic S was the dominant S pool.

Within the organic pool, carbon-bonded S was, in general, the predominant S form, accounting for >50% of total S in 16 out of 25 uppermost mineral soil horizons investigated (Table 2). With increasing depth, carbon-bonded S was found as the major form of organic S in 5 out of 9 intermediate horizons (Table 3) and in 9 out of 15 lowermost horizons (Table 4). Similar observations were made by David et al. (1983, 1987) and by Mitchell et al. (1986). Exceptions to this trend include the Fullerton, Tarklin, and Indian Gap sites with respect to the intermediate horizons and in the lowermost horizons, the Coweeta mixed deciduous, Nolan Divide, B.F. Grant Forest, and Indian Gap sites.

In general, adsorbed sulfate was only a minor S pool at all depths examined. In the uppermost horizon, this form of S comprised <13% total S in all sites investigated (Table 2). In intermediate soil horizons, the adsorbed anion accounted for <10% of total S in 5 out of 9 horizons studied (Table 3), with the exceptions being the Coweeta mixed deciduous B horizon, the Norway spruce Bs horizon, the Tarklin A/B horizon, and the B. F. Grant Forest A/B horizon. In the lowermost horizon, the adsorbed sulfate pool as a percentage of total S increased relative to the upper horizons, but this pool size was still much smaller than the organic pool in all but the B.F. Grant site (Table 4).

The dynamic nature of the S cycle in forest soils is demonstrated by the temporal variability observed in the pool sizes of various S fractions in the uppermost soil horizons. For example, from 1985 to 1988, carbon-bonded S in the B.F. Grant Forest A horizon decreased from 103 to 12 μg S/g dry weight, while adsorbed and insoluble ester sulfate levels increased from 8 to 22 and from 11 to 47 μg S/g dry weight, respectively (Table 2). Similar trends were observed for the Nolan Divide, Becking, Indian Gap, and Fullerton sites, where substantial changes in all S fractions existed between sampling dates (Table 2). This is probably due to variation in biological activity occurring with time, because for the Indian Gap site, no significant change in total S levels was observed between sampling dates; however, the levels of carbon-bonded S in the A horizon of this site decreased dramatically (Table 2). Previous research (Strickland and Fitzgerald 1983; Fitzgerald et al. 1988a) demonstrated that the mineralization of carbon-bonded S is biologically mediated, and this supports the above hypothesis.

In summary, organic S was the major pool in almost all sites examined regardless of depth. Conversely, adsorbed sulfate represented a small S pool relative to organic S at all depths. Cognizant of this observation, and noting additionally that carbon-bonded S accounted for most of this organic S at most sites examined at all depths studied, it seems logical to conclude that in terms of sulfur status, organic S formation is a more important S retention mechanism with increasing depth than is sulfate adsorption. This is surprising because in studies comparing laboratory derived potentials for each process (Fitzgerald et al. 1988b; Watwood et al. 1988), sulfate adsorption potentials exceeded those for organic S formation, especially in samples analyzed

TABLE 3. Intrinsic sulfur status of intermediate (20–40 cm) mineral soil horizons of various forested study sites

Site; horizon	Year sampled	Total sulfur	Total organic sulfur	Carbon-bonded sulfur	Adsorbed ester sulfate	Soluble ester sulfate	Insoluble ester sulfate	Adsorbed sulfate	Soluble sulfate
Mixed deciduous; B	1985	184	153 (83.3)	114 (61.8)	ndt	ndt	ndt	27.4 (14.9)	3.4 (1.8)
B. F. Grant Forest A/B	1988	213	96.9 (45.6)	95.7 (45.0)	nd	nd	1.2 (0.6)	98.5 (46.3)	17.1 (8.1)
Nolan Divide; A/B	1986	385	367 (95.3)	195 (50.7)	71.3 (18.5)	13.9 (3.6)	86.6 (22.5)	11.6 (3.0)	6.6 (1.7)
Becking; A/B	1986	827	783 (94.6)	525 (63.5)	56.2 (6.8)	55.4 (6.7)	146 (17.6)	38.0 (4.6)	6.6 (0.8)
Fullerton; A/B	1986	257	229 (88.8)	102 (39.6)	23.9 (9.3)	10.3 (4.0)	92.5 (35.9)	18.8 (7.3)	10.0 (3.9)
Tarklin; A/B	1986	239	192 (80.3)	37.3 (15.6)	1.7 (0.7)	20.8 (8.7)	132 (55.3)	42.1 (17.6)	5.0 (2.1)
Norway spruce; Bs	1987	143	83.5 (58.5)	74.5 (52.2)	nd	2.4 (1.7)	6.6 (4.6)	54.0 (37.8)	5.2 (3.7)
Norway spruce; B,C	1987	112	94.8 (84.5)	62.8 (56.0)	32.0 (28.5)	nd	nd	11.1 (9.9)	6.2 (5.6)
Indian Gap; A/B	1986	718	672 (93.5)	221 (30.7)	39.5 (5.5)	19.4 (2.7)	392 (54.6)	30.9 (4.3)	15.8 (2.2)

NOTE: Results are expressed as means of μg sulfur/g dry wt. with $n = 3$. SE < 15% in all cases. Values in parentheses represent the percentage of total sulfur. nd, not detected; ndt, not determined.

TABLE 4. Intrinsic sulfur status of lowermost (40+ cm) mineral soil horizons of various forested study sites

Site; horizon	Year sampled	Total sulfur	Total organic sulfur	Carbon-bonded sulfur	Adsorbed ester sulfate	Soluble ester sulfate	Insoluble ester sulfate	Adsorbed sulfate	Soluble sulfate
Mixed deciduous; C	1985	268	216 (80.5)	44.8 (16.7)	ndt	ndt	ndt	50.3 (18.7)	1.9 (0.7)
Duke Forest; B2	1987	1300	888 (67.9)	540 (41.2)	nd	nd	349 (26.7)	392 (29.9)	28.5 (2.2)
B. F. Grant Forest; Bt	1988	179	38.3 (21.4)	5.9 (3.3)	25.3 (14.1)	7.1 (4.0)	nd	141 (78.6)	nd
Red alder; B3	1987	267	241 (90.4)	134 (50.3)	31.4 (11.8)	2.2 (0.9)	73.2 (27.4)	21.7 (8.1)	4.0 (1.5)
Camp branch; C	1987	340	306 (90.2)	194 (57.1)	28.7 (8.4)	6.5 (1.9)	77.3 (22.8)	29.0 (8.5)	4.3 (1.3)
Nolan Divide; B	1986	572	314 (55.0)	251 (43.9)	18.6 (3.2)	44.9 (7.9)	nd	239 (41.9)	17.9 (3.1)
Nolan Divide; B	1987	811	596 (73.5)	41.5 (5.1)	nd	44.6 (5.5)	510 (62.9)	195 (24.0)	19.9 (2.5)
Becking; B	1986	495	389 (78.6)	179 (36.0)	23.7 (4.8)	19.2 (3.9)	168 (33.9)	95.6 (19.3)	10.6 (2.1)
Whiteface Mtn.; Bs	1987	1140	1090 (95.9)	877 (77.0)	26.3 (2.3)	nd	189 (16.6)	31.4 (2.8)	15.1 (1.3)
Fullerton; B	1986	360	324 (90.0)	314 (87.3)	10.1 (2.7)	nd	nd	17.8 (5.0)	17.9 (5.0)
Tarklin; B	1986	240	208 (86.8)	101 (42.0)	23.5 (9.8)	5.4 (2.3)	78.6 (32.6)	22.9 (9.6)	8.8 (3.7)
Loblolly pine; B	1986	130	114 (87.6)	34.6 (26.6)	26.2 (20.2)	16.9 (13.0)	36.0 (27.8)	4.2 (3.2)	12.0 (9.2)
Norway spruce; C	1987	91.4	73.6 (80.5)	50.3 (55.1)	18.6 (20.3)	4.7 (5.1)	nd	11.8 (12.9)	6.0 (6.6)
Indian Gap; B	1986	661	435 (65.7)	144 (21.8)	74.0 (11.2)	11.4 (1.7)	205 (31.0)	221 (33.5)	5.3 (0.8)
Florida; C	1988	433	397 (90.2)	339 (78.3)	23.6 (5.4)	11.6 (2.7)	22.7 (5.2)	21.4 (4.9)	15.3 (3.5)

NOTE: Results are expressed as means of μg sulfur/g dry wt. with $n = 3$. SE < 15% in all cases. Values in parentheses represent the percentage of total sulfur. nd, not detected; ndt, not determined.

for S in the current study (A.R. Autry and J.W. Fitzgerald, unpublished results). Results of field incubations with ³⁵S-labelled sulfate (Strickland et al. 1986) show that although most (80%) of the added label was adsorbed initially, subsequent incubation resulted in a decrease in the adsorbed S pool concomitant with an increase in the organic S pool. Sulfate adsorption may, therefore, represent a mechanism for immediate retention of incoming sulfate subsequent to desorption and incorporation of the anion into organic matter. Clearly, further study of the desorption process is needed before the true relevance of the adsorption process can be fully appreciated.

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