Influence of sampling date and substrate on nitrogen mineralization: comparison of laboratory-incubation and buried-bag methods for two Massachusetts forest soils[1]

RICHARD D. BOONE

Harvard Forest, Harvard University, P.O. Box 68, Petersham, MA 01366, U.S.A.

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Nitrogen (N) mineralization potential and net N mineralization *in situ* were measured monthly over 7 months for the forest floor horizons (Oi, Oe, Oa) and mineral soil (0–15 cm) of a pine stand and the mineral soil (0–15 cm) of a maple stand in Massachusetts, United States. In all cases, N mineralization potential per unit organic matter (anaerobic laboratory incubation) varied significantly by sampling month but was unrelated to the seasonal pattern for net N mineralization (buried-bag method). The organic horizons in the pine stand exhibited the most variable N mineralization potential, with the Oe horizon having more than a fourfold seasonal range. For the pine stand the Oe horizon also had the highest N mineralization potential (per unit organic matter) and the highest net N mineralization *in situ* (per unit area). In general, temporal and depth-wise variability should be considered when sites are assessed with respect to the pool of mineralizable N.

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Le potentiel de minéralisation de l'azote (N) et la minéralisation nette de N *in situ* ont été mesurés mensuellement sur un période de 7 mois pour les horizons de la couverture morte (Oi, Oe, Oa) et le sol minéral (0–15 cm) d'un peuplement de pin et le sol minéral (0–15 cm) d'un peuplement d'érable dans le Massachusetts, aux États-Unis. Dans tous les cas, le potential de minéralisation de N par unité de matière organique (incubation anaérobie au laboratoire) a varié significativement avec le mois d'échantillonnage mais n'a pas été relié au patron saisonnier pour la minéralisation (méthode du sachet enfoui). Les horizons organiques dans le peuplement de pin ont exhibé le potentiel de minéralisation de N le plus variable, avec l'horizon Oe ayant une étendue saisonnière d'un facteur de quatre. Pour le peuplement de pin, l'horizon Oe avait aussi le plus haut potentiel de minéralisation de N (par unité de matière organique) et le plus haut taux de minéralisation nette de N *in situ* (par unité de surface). En général, la variabilité temporelle et selon la profondeur devrait être considérée quand des stations sont évaluées en relation avec le pool de N minéralisable.

[Traduit par la rédaction]

Introduction

The quality of organic matter in forest soils, as reflected by the pool of readily mineralizable nitrogen (N), varies by horizon and depth (Federer 1983; Binkley and Hart 1989) and has been shown to vary with sampling time (Adams and Attiwill 1986; White *et al.* 1988; Binkley and Hart 1989). Such spatial and temporal changes, though not commonly documented, help define reference conditions for a site. This variability, especially if large, may be relevant to N mineralization modeling efforts, investigations of forest-soil profile development, and use and interpretation of N availability indices.

Here, for a pine stand and a maple stand in western Massachusetts, United States, I evaluate N mineralization potential (laboratory anaerobic incubation) for differences by sampling month, then compare the temporal pattern with that for net N mineralization *in situ* (buried-bag method) measured over the same time period. By both measures, I also examine depth-wise changes in the upper profile of the pine stand. All results reported here represent base-line information gathered for a study on the contribution of light fraction soil organic matter to N availability (Boone 1989).

Materials and methods

Study sites were in the Mount Toby Forest (owned and managed by the University of Massachusetts) within the towns of Sunderland and Leverett in west-central Massachusetts. The pine site is a pure stand of even-aged white pine (*Pinus strobus* L.) that seeded naturally from old-field pines during the early 1920s. The stand was thinned seven times between 1942 and 1977, but a moderately high basal area (>37.5 m^2/ha) has been maintained. The understory is open but has a few black birch (*Betula lenta* L.) and white ash (*Fraxinus americana* L.) saplings. Canada mayflower (*Maianthemum canadense* Desf.) forms a dense carpet over the forest floor every spring. The maple site supports a nearly pure stand of mature, even-aged sugar maples (*Acer saccharum* Marsh.). It is in a small bowl roughly 1 km south of the pine site and is bordered by a seasonal stream that leads to a nearby pond. The understory is dominated by a moderately dense population of spice bush (*Lindera benzoin* (L.) Blume) about 2 m tall. Both study areas are part of a generally level tract that was farmed for tillage or pasture until the mid-1800s to early 1900s (Rhodes 1979).

Soil at the two sites (Table 1) is a sandy loam (40–50 cm deep), most likely of aeolian origin, on top of a glacial outwash of sand, gravel, and cobbles. The pine site has a mor soil with clearly discernible Oi (0–1 cm depth), Oe (1–4 cm depth), and Oa (4–5 cm depth) horizons. Equivalent weights were 6.5 (Oi), 14.2 (Oe), and 20.8 (Oa) Mg/ha; organic matter was 6.2 (Oi), 12.1 (Oe), and 10.4 (Oa) Mg/ha. Except for a small number of beetles and ants, the pine soil appears to have a negligible population of macro-invertebrate mixers. The maple site has a mull soil with a single organic horizon of loose litter and an abundant earthworm population. Litter dropped on the site in September and October is essentially absent from the soil surface by the end of the following summer. Both sites have relict Ap horizons, indicating past cultivation activity. The deeper cobbly outwash at the sites is derived from Triassic-age conglomerate and sandstone (Rhodes 1979).

Net N mineralization *in situ* was measured by sequential buried-bag incubations (Eno 1960; Nadelhoffer *et al.* 1983; Raison *et al.* 1987) from April 1986 to April 1987 for a 25 by 25 m plot in the

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[1] Contribution from the Department of Forestry and Wildlife Management, University of Massachusetts, Amherst, MA 01003, U.S.A.

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TABLE 1. Soil properties at the pine and maple study sites

Property	n	Pine	Maple
Soil type	—	Mor	Mull
Soil series	—	Merrimac	Merrimac
Soil family	—	Sandy, mixed, mesic, Typic Dystrochrept	Sandy, mixed, mesic, Typic Dystrochrept
Soil texture	8	Sandy loam (49% sand, 47% silt, 4% clay)	Sandy loam (58% sand, 41% silt, 1% clay)
Organic matter (%)	56	6.44 (0.07)	7.29 (0.15)
pH (1:2, soil:water)	8	4.3 (0.2)	5.4 (0.7)
Bulk density (g/cm^3)	56	0.89 (0.01)	0.91 (0.01)
Coarse fragments (%)*	56	16.15 (1.02)	13.38 (1.39)

NOTE: Measured characteristics (means with 1 SE in parentheses) are for the mineral soil (0–15 cm depth).
*Per mineral soil (<2 mm) weight.

white pine stand and a 30 by 30 m plot in the sugar maple stand. Within the pine plot, two 2-point composite samples of each forest floor horizon (Oi, Oe, Oa) were collected individually at eight locations chosen randomly every month; the only exception was that Oi material was not collected in April 1986. Material, including roots, beneath a 15 by 15 cm template carefully was cut and scraped away at each composite point and sealed in a polyethylene bag (0.025 mm thickness). Additionally, four cores (5.1 cm diameter by 15.0 cm deep) at each location were collected with a steel corer containing a plastic sleeve (1-mm wall thickness), extracted within the sleeve, and sealed in polyethylene bags. Sleeves for *in situ* cores were perforated with 2-mm holes spaced at 0.5 hole/cm^2. Per location, one bag each for Oi, Oe, and Oa horizons plus two mineral soil cores were stored in a cooler for transport to the laboratory; these were regarded as time zero (t_0) samples and represented initial conditions. The second bag of each forest floor horizon and the second two mineral soil cores were weighed, placed inside a fine-mesh dacron sack to prevent puncture of the polyethylene bags by insects, and returned to the ground for *in situ* incubation. Net N mineralization accordingly is the increase in (NH_4^+ + NO_3^-)-N during the incubation. The procedure at the maple site was the same, except that only the mineral soil (0–15 cm depth) was sampled. Incubation intervals ranged from 25 to 39 days (mean = 33 days) from April to October for the two sites; the overwinter incubation (October 1986–April 1987) was 172 days for the pine site and 169 days for the maple site. Sampling at both sites was continuous over the 12-month period.

Forest-floor and mineral-soil samples taken to the laboratory were analyzed for inorganic N, after storage at 3°C for a maximum of 3 days, or immediately upon thawing, following storage at −10°C. For t_0 and incubated samples, duplicate subsamples (wet weights: Oi and Oe, 3.0 g; Oa, 5.0 g; <2 mm composite of the two mineral soil cores, 10.0 g) were shaken with 100 mL 2 M KCl for 1 h (Keeney and Nelson 1982), then filtered through a Gelman prefilter and Whatman 42 filter paper. Roots >10 mm length were picked from the organic horizons before the extraction. Extracts were analyzed for ammonium N (NH_4^+-N) and nitrate N (NO_3^--N) by the Berthelot reaction and cadmium reduction, respectively, on a Technicon AutoAnalyzer II (Technicon Industrial Methods 1977, 1978). Periodic checks indicated no detectable levels of nitrite in samples analyzed for nitrate. Values for net N mineralization are expressed both per unit organic matter (OM), determined by loss on ignition (Davies 1974), and per unit area.

Nitrogen mineralization potential by anaerobic incubation (Keeney 1982) was measured for the t_0 samples collected monthly from April 1986 to October 1986. After each t_0 soil was sampled for inorganic N extraction, additional triplicate subsamples (wet weights: Oi and Oe, 1.0 g; Oa, 3.0 g; <2 mm mineral soil, 10.0 g) were combined with 12.5 mL distilled and deionized water, incubated 7 days in stoppered test tubes at 40°C, and filtered as above. Extracts from the anaerobic incubations were analyzed for NH_4^+-N alone, as NO_3^--N is not produced under anaerobic conditions. Nitrogen mineralization potential, expressed per unit OM, is the difference between NH_4^+-N present before and after incubation. Monthly means for N mineralization potential and N mineralization *in situ* were tested for significant differences with the ANOVA program of the personal computer SAS system (SAS Institute Inc. 1987).

Results

The Oe and Oa horizons and the mineral soil at the pine site exhibited seasonal and unrelated patterns of net N mineralization *in situ* and N mineralization potential (Fig. 1). Net N mineralization, except in the Oi horizon, increased to a peak in July, then declined to a minimum in October. By contrast, N mineralization potential peaked in May, then fell to a minimum in August. The peak of net N mineralization *in situ* thus was nearly coincident with the minimum for N mineralization potential. The seasonal range for N mineralization potential was nearly twofold for the mineral soil, nearly threefold for the Oa horizon, and more than fourfold for the Oe horizon (Table 2). The Oi horizon showed little change and an irregular pattern for both N mineralization measures, with peaks in May and August and minimum values in the fall. Differences in N mineralization potential among months, for all organic horizons and the mineral soil, were significant ($p < 0.01$, ANOVA).

Highest net N mineralization *in situ* (Fig. 1) generally occurred in the Oe and Oa horizons, while the Oe horizon alone markedly exhibited the highest N mineralization potential. In decreasing order of importance, the sequence for the organic horizons and mineral soil was Oe and Oa > Oi > mineral soil (*in situ* activity) and Oe > mineral soil and Oa > Oi (potential). On an area basis (Table 3), net N mineralization for the entire 1-year period (April 1986 to April 1987) was 4.3 (Oi), 36.1 (Oe), 27.5 (Oa), and 21.7 (mineral soil, unsieved) kg N/ha, for a total of 89.6 kg N/ha. Nitrification at the pine stand was undetectable in the Oi and Oe horizons and just barely measurable (<3 mg NO_3^--N/kg sample) in the Oa horizon (overwinter only) and mineral soil (August only).

At the maple site, N mineralization potential of the mineral soil varied irregularly over the sampling period, while net N mineralization *in situ* peaked in July, but was lower otherwise (Fig. 2). In general, seasonal changes in the two mineralization measures, each indicating significant differences ($p <$ 0.01), were unrelated. On an area basis (Table 4), mineral soil at the maple site yielded 107.9 kg N/ha (net) for the 12-month

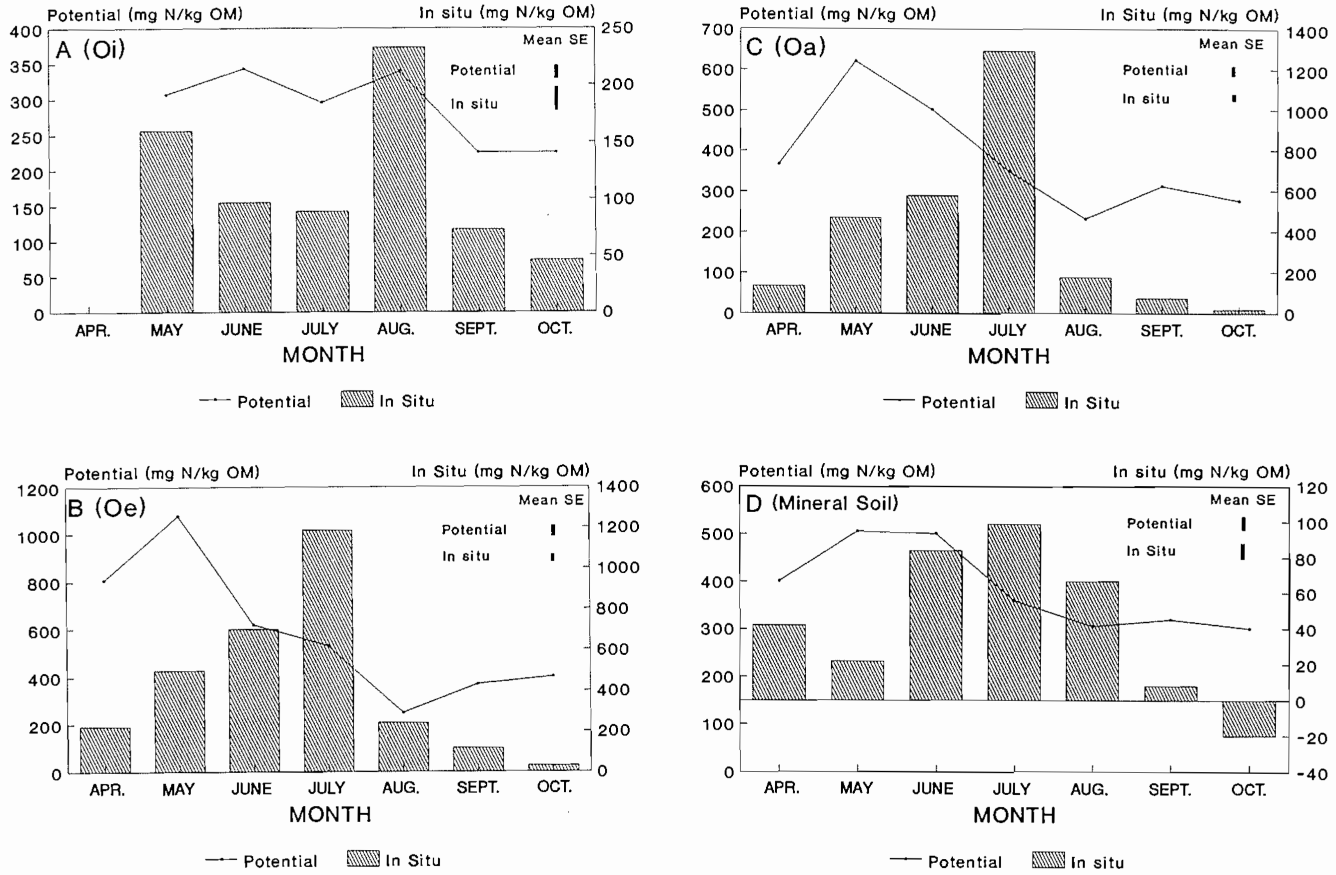

FIG. 1. Seasonal patterns of net N mineralization *in situ* and N mineralization potential, both expressed per unit organic matter, for the (A) Oi horizon, (B) Oe horizon, (C) Oa horizon, and (D) mineral soil (0–15 cm depth) in the pine stand. Values are monthly means. NH_4^+-N represents more than 99% of the bar values for the *in situ* activity. Note that the *y*-axis scale for the four figures is not the same.

TABLE 2. Nitrogen mineralization potential (anaerobic incubation) for the pine and maple stands (mg N/kg organic matter)

	Pine				Maple
	Oi	Oe	Oa	Mineral soil	Mineral soil
April	nd	807 (75)	382 (55)	408 (39)	1057 (47)
May	313 (20)	1067 (104)	598 (63)	509 (35)	1224 (64)
June	348 (30)	617 (53)	524 (68)	516 (53)	1110 (43)
July	318 (34)	548 (32)	380 (40)	347 (26)	834 (81)
August	345 (28)	236 (42)	237 (17)	328 (35)	1232 (52)
September	232 (17)	361 (22)	282 (19)	318 (38)	737 (50)
October	227 (15)	397 (27)	252 (10)	294 (21)	1007 (16)
Mean	297	576	379	389	1029
SD	54	286	138	92	187
SE	22	108	52	35	71
CV	18	50	36	24	18

NOTE: Values are monthly means with 1 SE in parentheses ($n = 8$).

period. NO_3^--N represented about half the net inorganic N produced during most *in situ* incubations. Nitrogen mineralization from mineral-soil OM, by both buried-bag and laboratory techniques, was two to five times greater for the maple site than for the pine site.

Discussion

Organic matter quality at the pine and maple stands, as indicated by the pool of mineralizable N, is strongly dependent on sampling time or season and did not control the seasonal course of N mineralization *in situ*. This finding lends support to the few other studies that similarly have reported

TABLE 3. Net N mineralization *in situ* in the organic horizons and mineral soil (0–15 cm depth) of the pine stand (kg N/ha)

	Oi	Oe	Oa	Mineral soil	Total
April	nd	2.7 (0.4)	1.3 (0.2)	3.0 (0.3)	7.0
May	1.0 (0.2)	6.0 (1.3)	4.7 (5.8)	1.6 (1.0)	13.3
June	0.6 (0.1)	8.4 (0.5)	5.8 (0.5)	6.0 (0.4)	20.8
July	0.6 (0.2)	14.3 (0.6)	12.9 (0.8)	7.1 (0.5)	34.9
August	1.4 (0.2)	2.9 (0.5)	1.8 (0.3)	4.8 (1.5)	10.9
September	0.4 (0.3)	1.4 (0.3)	0.8 (0.2)	0.6 (0.4)	3.2
October	0.3 (0.1)	0.4 (0.3)	0.2 (0.3)	−1.4 (0.5)	−0.5
Sum	4.3	36.1	27.5	21.7	89.6

NOTE: Values are means with 1 SE in parentheses ($n = 8$). NH_4^+-N represents >99% of the inorganic N that accumulated in the organic horizons and mineral soil during the incubation period. Values for the mineral soil were corrected for coarse fragments >2 mm in diameter that were collected with the soil corer.

TABLE 4. Net N mineralization *in situ* in the mineral soil (0–15 cm depth) of the maple stand (kg N/ha)

	NH_4^+-N	NO_3^--N	Total
April	12.9 (1.1)	3.2 (0.5)	16.1 (1.6)
May	10.7 (0.3)	11.4 (3.6)	22.1 (3.9)
June	12.3 (1.5)	7.2 (1.3)	19.5 (2.8)
July	26.5 (2.2)	12.8 (2.1)	39.3 (4.3)
August	9.0 (0.8)	8.3 (0.8)	17.3 (1.6)
September	−6.5 (1.3)	2.7 (0.8)	−3.8 (2.1)
October	−6.8 (0.5)	4.2 (1.5)	−2.6 (2.0)
Sum	58.1	49.8	107.9

NOTE: Values are means with 1 SE in parentheses ($n = 8$). The values have been corrected for coarse fragments > 2mm diameter that were collected with the soil corer.

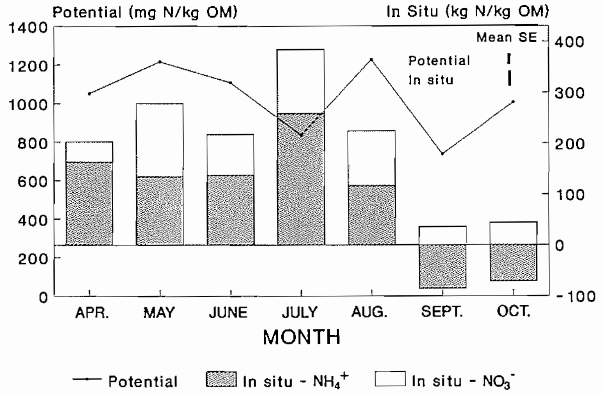

FIG. 2. Seasonal patterns of N mineralization potential and net N mineralization *in situ*, both expressed per unit organic matter, for the mineral soil (0–15 cm depth) of the maple stand. Values are monthly means.

coincident seasonal courses for both substrate quality (aerobic laboratory incubation only) and N mineralization *in situ* in forest soils (Vitousek and Matson 1985; Carlyle and Malcolm 1986). Vitousek and Matson (1985) show nearly a 10-fold seasonal range for N mineralization potential (0–15 cm, mineral soil) for a clear-cut pine site but found that temperature and moisture were the primary controls on the seasonal course for net N mineralization *in situ*. The N mineralization pattern for the Massachusetts sites, though unrelated to monthly changes in the moisture content of the buried bags (Table 5), does correspond to the seasonal soil temperature regime for the region. At most, spring mineralization in the pine stand (Oi excluded) was enhanced somewhat by correspondingly higher N mineralization potentials. Notably, others (Popovic 1971; Vitousek and Matson 1985) have shown that the seasonal pattern for N mineralization potential can vary from year to year, suggesting that similar temporal patterns for substrate quality and N mineralization *in situ* are possible.

Reasons for the changes in N mineralization potential, all within ranges previously reported (Ohta and Kumada 1978; Shumway and Atkinson 1978; Smith *et al.* 1981), may be suggested by consideration of what the anaerobic incubation technique actually measures. Recent studies that have compared N release upon chloroform-fumigation incubation and anaerobic incubation (Azam *et al.* 1988; Myrold 1987) suggest that the anaerobic technique primarily measures N in the biomass of killed aerobic microflora, a strong indicator of available N. Accordingly, the variation in N mineralization potential observed for both sites may reflect fluctuating levels of microbial N, together perhaps with labile non-microbial material. If so, microbial N peaked in the spring in the pine stand, consistent with the expected microbial population pattern for continental climates (Lowe and Paul 1970), and varied irregularly by season in the maple stand. Clearly, any future investigations examining the seasonality of the readily mineralizable N pool should consider microbial biomass assessments.

The pine stand, in addition to temporal changes, illustrated variability by horizon or depth with respect to substrate quality and net N mineralization *in situ*. The Oe layer, composed mostly of foliar litter at an intermediate stage of litter decomposition, released the most mineralizable N *in situ*. The Oe was second to the Oa by unit mass, but had the larger pool of readily mineralizable N (Table 2) and always a higher gravimetric moisture content (Table 5). The importance of the Oe horizon as a N source, reported also by others (Ohta and Kumada 1978; Federer 1983), is consistent with decomposition models (Aber *et al.* 1990) that predict slow N loss rates for the humified material characteristic of the Oa layer and mineral soil. Organic matter conventionally is regarded as progressively older and more recalcitrant with increasing depth (Federer 1983), though spodic horizons may represent an exception.

The Oi horizon is notable simply because it was a net N source. Numerous decomposition studies with mesh litter bags (Berg and Staaff 1981; Berg and Ekbolm 1983; McClaugherty *et al.* 1985) have consistently shown that fresh

TABLE 5. Gravimetric moisture content (%) of buried-bag material during *in situ* incubation

	Pine				Maple
	Oi	Oe	Oa	Mineral soil	Mineral soil
April	nd	244.9 (11.5)	138.5 (8.5)	36.0 (0.6)	34.5 (1.3)
May	132.7 (7.3)	177.7 (8.3)	155.1 (149.4)	31.8 (1.0)	31.5 (1.3)
June	164.8 (21.1)	245.8 (7.5)	149.4 (10.1)	33.1 (0.6)	38.0 (2.0)
July	48.8 (6.2)	130.1 (11.3)	76.0 (6.7)	19.8 (0.6)	34.3 (1.0)
August	149.9 (7.4)	223.0 (12.0)	129.4 (14.4)	29.1 (1.0)	30.6 (1.2)
September	110.8 (106.1)	193.5 (13.4)	115.1 (2.7)	17.5 (1.4)	21.9 (0.9)
October	106.1 (10.4)	228.5 (10.1)	120.3 (7.4)	20.8 (0.9)	34.2 (0.9)

NOTE: Values are means with 1 SE in parentheses ($n = 8$). Mean weight change of material from start to end of incubations was <1%. The Oi horizon at the maple stand was not sampled.

litter is a net N immobilizer for 1–3 years. Surprisingly, the pine-stand Oi horizon, composed mainly of litter less than 1 year old, exhibited an appreciable N mineralization potential (7-month mean = 289 mg N/kg OM) and moderately high net N mineralization *in situ* (7-month mean = 116 mg N/kg OM). These unexpected mineralization results for the Oi are explained perhaps by the nature of the incubation methodologies. Mesh litter bags receive C and N inputs from precipitation (including throughfall) and from soil microflora, whereas incubating test tubes and buried bags do not. An additional factor relevant to the laboratory incubations is that anaerobic conditions stimulate N mineralization (Keeney 1982; Goh and Haynes 1986) while depressing N immobilization (Bartholomew 1965). Consequently, results here, though in agreement with other reports that Oi material can be a net N source (Ohta and Kumada 1978; Federer 1983), may primarily highlight methodology limitations.

In summary, this study provides further evidence that the pool of readily mineralizable N in forest soils, especially in the forest floor, can vary greatly with season and by horizon or depth. For site assessment and cross-site comparisons, recognition or examination of this variability would seem prudent.

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