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The chemical characteristics of soil in control and experimentally thinned plots in mesic oak forests along a historical deposition gradient

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Abstract

This study examined the variations in the chemical parameters of soils of seven forests located along a historical deposition gradient spanning 8.5° longitude from southern Illinois to central West Virginia. Four to six mature control plots were sampled on two of the sites, and two experimentally thinned and two control plots were sampled on the remaining five sites. Most soil properties varied significantly both among experimental forests and between control and thinned plots. Soil pH, Al, PO_4 and inorganic N were correlated with longitude, whereas differences in Ca, Mg and Ca:Al ratio among experimental forests were more closely linked to differences in parent materials. Nine of the 12 soil properties measured differed between control and thinned plots, and the variance explained by the proportion of basal area removed in the experimental thinnings was always greater than that explained by longitude or current basal area. Overall, thinned plots had greater soil pH, inorganic N, Ca, Mg, K and Ca:Al ratio, whereas control plots had greater Al and PO_4. These patterns of difference were also apparent when the chemical properties of soil of the experimental forests were analyzed individually. We suggest that thinning may have reduced uptake, increased relative nutrient availability, changed leaf and litter quality, and altered decomposition and mineralization rates in such a way as to produce persistent differences in soil properties. © 1997 Elsevier Science B.V.

1. Introduction

Over the last 50 yr, some forest soils in eastern North America have experienced decreases in pH, increases in NO_3 deposition and soil-solution concentration, increased soil-solution Fe and Al concentrations, and lowered Ca:Al ratio (Bondietti and McLaughlin, 1992), all of which could affect key ecosystem processes (Aber et al., 1989). In addition, when coupled with periodic stresses such as drought, these changes in the below-ground portions of the ecosystem could also affect tree growth and/or mortality.

Of particular interest is the potential impact of chronic additions of N to eastern forest ecosystems by atmospheric deposition. Under natural conditions, N-limited forest ecosystems (i.e., those with low rates of mineralization and little nitrification) are typically dominated by tree species that depend on ectomycorrhizae (ECM) (Vogt et al., 1991) such as oaks (*Quercus* spp.), pines (*Pinus* spp.) and spruces

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(*Picea* spp.). Because of the ability of the ECM to forage for NH_4, reduce NO_3 and degrade low-molecular weight organic N substrates, these tree species can maintain growth even under low-N conditions (France and Reid, 1983; Jansen, 1991). Heavy, chronic N deposition may greatly alter the N status of forest soils through its effect on leaching of Ca, mobilization of Al and removal of N limitation for tree growth. Under such conditions, ECM-dependent tree species may decline and be replaced by species that depend on arbuscular mycorrhizae (AM) that are more typical of N-rich forest sites (Jansen, 1991; Arnolds, 1991) such as maples (*Acer* spp.) and yellow poplar (*Liriodendron tulipifera*). Thus acidic deposition with a significant N component has the potential to affect eastern forest ecosystems over the long term, both in the chemical status of soil and in tree species composition.

Although reports of shifts in dominance by oaks (and other ECM-dependent tree species), AM-dependent tree species are common in the literature (e.g. Newman and Ebinger, 1985; Parker et al., 1985; Cho and Boerner, 1991) and instances of oak decline have been reported widely throughout this century (Millers et al., 1989), the mechanisms behind such shifts remain unclear. This study is part of a larger analysis of the relationship among forest management, drought responses, tree mortality and ecosystem function along the Ohio River Valley. Here, we report patterns of variation in the chemical characteristics of soil in mesic, oak-dominated forests in seven experimental forests from Illinois to West Virginia in relation to both longitude and experimental thinning. We also relate the results of these soil analyses to rates of nitrogen mineralization/nitrification and patterns of microbial abundance that were quantified as part of the larger study.

2. Methods

2.1. Study sites and field sampling

Seven experimental forests located in the Ohio River Valley were selected for study. These seven sites spanned 8.5° longitude (Table 1) along a gradient of historical atmospheric deposition which increased from west to east (Work Group One, 1983, Lovett, 1992). In 1992 and 1993, for example, H and NO_3 deposition from southern Illinois to central West Virginia increased from 29–41 to 65–72 kg H/ha/yr and from 9–15 to 21–22 kg NO_3/ha/yr (NADP/NTN, 1992, 1993). Mean annual precipitation, in contrast, varied only from 116 cm/yr in southern Illinois to 107 cm/yr in central West Virginia (Parks, 1975, Pyle et al., 1982). As a consequence of the differences in elevation (Table 1), however, the mean annual snowfall ranged from 33 cm in southern Illinois to 150 cm in central West Virginia (Parks, 1975, Pyle et al., 1982).

In the Bald Rock, McKee, Robinson, Mead, and Raccoon Experimental Forests, we selected four study plots for analysis. Two of the plots at each site had been established and thinned for experimental purposes in the early 1960's; the remaining two were established at that time as the paired control plots (Table 1). In addition, we sampled six long-term control plots in the Kaskaskia Experimental Forest and four randomly chosen plots in the Fernow Experimental Forest. Within an experimental forest, elevation, slope, aspect and soil type were as uni-

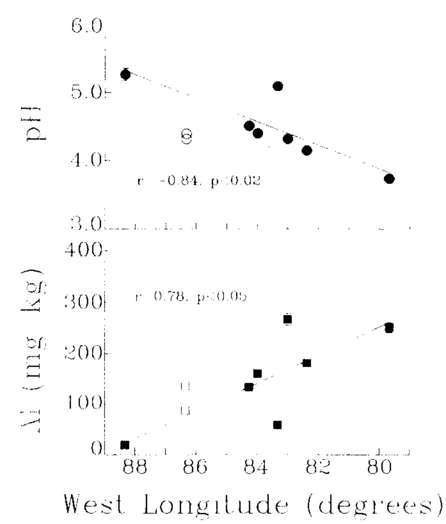

Fig. 1. Patterns of variation in A-horizon pH and KCl extractable Al (mg/kg dry soil) in soils from seven experimental forests in relation to longitude. Each data point represents $N = 72$; standard error bars were plotted but, in most cases, disappear within the points. The best fit regression line and 95% confidence intervals are shown. The two open points represent means of $N = 14$ samples from two similar stands in the Hoosier National Forest, Indiana analyzed by Boerner and LeBlanc (1995).

form as possible among the four study plots (Table 1).

All sites were on noncalcareous substrates, mostly siltstones and sandstone/siltstone/shale complexes, and all had clay loam or silty clay loam soils derived from residuum and colluvium. The soils dominating the plots in six of the seven experimental forests were classified as typic hapludults (ultisols) (Table 1). The soils at Kaskaskia, the westernmost of our study areas, were typic hapludalfs (alfisols), and some samples from the upper portions of plots in the Fernow, our easternmost study area, were typic dystrochrepts (inceptisols). There were no significant difference in soil texture among plots within any of the experimental forests (Boerner and Sutherland, 1995). Estimates from Soil Conservation Service surveys indicated that permeability varied only between 0.6–2.0 cm/h, except in some skeletal soils at Fernow in which permeability may have ranged up to 4.0 cm/h.

In each study plot we established two random quadrats and took nine random soil samples from each quadrat along a transect running parallel to the contour of the slope during a ten day period in July 1993 (total of 18 samples per plot and 72 per experimental forest). Before taking a sample, the forest

Table 1
Experimental forest study site names, locations, major soil series and orders for study plots in seven experimental forest sites. For each sample plot, the thinning treatment imposed in the 1960's (with final stocking percentages), elevation (m), aspect and slope angle (%) are given

Name	State	Latitude/longitude	Soil series	Soil order	Plots	Treatment	Elevation/aspect/slope
Kaskaskia	Illinois	37°32′N, 88°20′W	Alford–Baxter	typic hapludalfs	36A	all plots in this	500/NE/8%
					36B	site were control	460/NE/12%
					37	plots established	500/S/16%
					38	in 1935; select	460/SSW/16%
					42	cut in 1890-	460/NE/16%
					43	1910	460/NE/16%
Bald Rock	Kentucky	36°59′N, 84°16′W	Shelocta–Rigley	typic hapludults	2	control/80%	1070/ENE/22%
					5	thinned to 40%	1060/WNW/18%
					7	control/80%	1060/NNE/33%
					16	thinned to 20%	980/SSW/9%
McKee	Kentucky	37°27′N, 83°59′W	Shelocta–Gilpin	typic hapludults	3	control/75%	1180/SE/19%
					9	thinned to 30%	1270/ESE/38%
					10	control/75%	1270/E/25%
					13	thinned to 15%	1260/NNW/27%
Robinson	Kentucky	37°15′N, 83°20′W	Shelocta–Gilpin–Hazelton	typic hapludults	4	thinned to < 10%	1290/ESE/50%
					9	control/100%	1020/SE/60%
					11	control/100%	1045/SSE/50%
					18	thinned to < 10%	1400/ESE/40%
Mead	Ohio	39°15′N, 83°00′W	Shelocta–Brownsville	typic hapludults	1	thinned to 40%	665/SE/30%
					6	control/80%	760/SE/15%
					8	thinned to 50%	850/S/30%
					9	control/100%	790/SE/15%
Raccoon	Ohio	39°10′N, 82°23′W	Gilpin–Steinsburg	typic hapludults	8	thinned to 50%	890/WNW/20%
					10	control/100%	860/W/11%
					13	thinned to 40%	800/WNW/14%
					16	control/80%	790/NNW/29%
Fernow	West Virginia	39°03′N, 79°41′W	Gilpin–DeKalb	typic hapludults and typic dystrochrepts	1A	all plots in this	2570/E/6%
					2A	site were controls	2660/SE/8%
					3A	established after	2730/ENE/6%
					4A	high-grading in 1905–1910	2700/ESE/9%

Table 2
Two-way analysis of variance of the chemical properties of soil in relation to experimental forest site, stand management and their interaction. TIN is the sum of NO_3 and NH_4; Ca:Al is expressed as the molar ratio. $N = 360$ for all soil chemical properties except Fe ($N = 327$) and Pb ($N = 189$). No transformations were required to meet the assumptions of the ANOVA model

Variance components	Soil chemical property											
	pH	NO_3	NH_4	TIN	PO_4	Ca	Mg	K	Al	Ca:Al	Fe	Pb[a]
Experimental forests	****	****	****	****	****	****	****	****	****	****	****	
Thinning treatment	****	****	*	****	****	****	****	****	****	****	ns	ns
Interaction	****	****	***	****	****	ns[a]	****	****	**	****	ns	ns

Significant codes are: **** $p < 0.0001$; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = difference not significant at $p < 0.05$.
[a] $F = 1.99$, $p < 0.096$.

Table 3
Soil chemical conditions in seven experimental forests. Within a column, means followed by the same lower case letter were not significantly different. $N = 72$ for each experimental forest and standard errors of the means are given in parentheses. NO_3, NH_4 and Al were measured in 2 M KCl extracts and Ca, Mg, K, Fe, P and Pb in 1 M NH_4OAc. All parameters except pH and Ca:Al ratio are in mg/kg dry soil. Experimental forests are listed in order of decreasing mean pH

Experimental forest	pH	NO_3	NH_4	Al	Ca	Ca:Al molar ratio
Kaskaskia (IL)	5.27 a	2.22 b	0.65 e	18.86 e	649.94 a	141.55 a
	(0.09)	(0.51)	(0.09)	(3.18)	(34.42)	(18.58)
Robinson (KY)	5.10 a	1.38 bc	1.30 cd	58.69 d	582.64 a	90.82 b
	(0.07)	(0.22)	(0.10)	(9.41)	(50.09)	(17.15)
Bald Rock (KY)	4.51 b	0.45 de	1.62 bc	134.54 c	117.69 b	12.25 c
	(0.07)	(0.08)	(0.13)	(7.17)	(17.69)	(6.25)
McKee (KY)	4.40 b	1.22 cd	1.96 b	161.37 bc	122.88 b	1.48 c
	(0.04)	(0.10)	(0.14)	(8.48)	(14.21)	(0.62)
Mead (OH)	4.32 bc	0.40 de	1.54 bc	267.35 a	146.86 b	0.76 c
	(0.03)	(0.08)	(0.10)	(11.38)	(16.02)	(0.24)
Raccoon (OH)	4.15 c	0.66 e	0.92 de	182.06 b	76.63 b	0.37 c
	(0.03)	(0.02)	(0.08)	(6.12)	(9.52)	(0.10)
Fernow (WV)	3.74 d	4.96 a	2.39 a	252.32 a	159.88b	0.57 c
	(0.04)	(0.33)	(0.17)	(10.24)	(14.88)	(0.08)

Experimental forest	Mg	K	P	Fe	Pb
Kaskaskia (IL)	83.93 b	82.98 b	1.15 c	0.22[a] c	0.13[b] c
	(3.74)	(2.45)	(0.04)	(0.02)	(0.02)
Robinson (KY)	125.38 a	101.87 a	1.52 b	0.35 c	0.16 bc
	(7.90)	(2.45)	(0.05)	(0.03)	(0.03)
Bald Rock (KY)	38.35 c	69.62 c	1.14 c	0.97 b	0.40 ab
	(6.72)	(4.25)	(0.06)	(0.13)	(0.09)
McKee (KY)	26.99 cd	69.36 c	1.26 c	0.46 bc	0.18 bc
	(2.55)	(2.73)	(0.05)	(0.04)	(0.02)
Mead (OH)	38.40 c	81.10 b	1.25 c	0.36 c	0.20 bc
	(3.21)	(2.65)	(0.06)	(0.02)	(0.01)
Raccoon (OH)	15.21 d	53.13 d	1.26 c	0.61 bc	0.22 bc
	(1.34)	(2.81)	(0.06)	(0.03)	(0.07)
Fernow (WV)	26.23 cd	79.77 bc	1.75 a	2.19 a	0.45 a
	(1.28)	(3.11)	(0.06)	(0.27)	(0.05)

[a] Not all samples had Fe detectable at the detection limit of 0.10 mg/kg; $N = 31$ for Kaskaskia, $N = 60$ for Robinson, $N = 70$ for Bald Rock, $N = 69$ for McKee, $N = 58$ for Mead, $N = 70$ for Raccoon and $N = 72$ for Fernow.
[b] Not all samples had Pb detectable at the detection limit of 0.075 mg/kg; $N = 13$ for Kaskaskia, $N = 34$ for Robinson, $N = 33$ for Bald Rock, $N = 35$ for McKee, $N = 43$ for Mead, $N = 44$ for Raccoon and $N = 62$ for Fernow.

floor (litter + unconsolidated humus) was cleared from the mineral soil surface over an area of approximately 0.25 m^2. A 2-cm soil corer was then used to extract A-horizon cores of 5–10 cm in length, depending on the forest site. Each sample was a composite of 5–15 such A-horizon cores totaling at least 200 g fresh mass. We limited our sampling to the A-horizon because rates of nutrient and organic matter turnover that might affect tree growth are typically much greater in the A- than in the B-horizon and unconsolidated litter (Boerner and Koslowsky, 1989). All samples were transported to the laboratory under refrigeration.

2.2. Laboratory methods

Each sample was subdivided into two subsamples. One was sent to Micro-Macro International (Athens, Georgia) for analysis of soil texture by hydrometer, pH in water, Ca, Mg, K, Pb and Fe in 1 M NH_4OAc extracts, and PO_4 and Al in 1 M KCl extracts. Methods followed Jones (1992). The second subsample was extracted with 1 M KCl and analyzed for NH_4 and NO_3 by calorimetric techniques with a Lachat QuikChem Autoanalyzer. Total inorganic N (TIN) was calculated as the sum of NH_4 and NO_3.

2.3. Statistical analysis

Our first step was to compare soil chemical parameters among the seven experimental forests, among stands within forests, and in relation to thinning by analysis of variance (ANOVA). The unit of replication was the plot and individual soil samples were considered to be subsamples within plots. In the ANOVA, therefore, mean squares for main effects were tested against the interaction mean square rather than against the residual error mean square. We used the Ryan–Einot–Gabriel–Welsch Modified *F* Test to posttest differences among means where

Table 4
Forward selection, stepwise regression of soil parameters for five experimental forests in relation to longitude, the proportion of basal area removed during thinning in the 1960's and the current basal area (as of 1992–1993). For each soil parameter, the full model r^2/p value and the p value/partial r^2 for each main effect are given. $N = 360$

Parameter	Total model r^2	Longitude	Proportion of basal area removed	Current basal area
pH	0.275	0.030	0.244	ns
	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	
NO_3	0.336	0.040	0.296	ns
	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	
NH_4	0.108	0.079	ns	0.029
	$p < 0.0001$	$p < 0.0001$		$p < 0.0007$
TIN	0.310	0.105	0.180	0.025
	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0004$
Ca	0.605	ns	0.605	ns
	$p < 0.001$		$p < 0.001$	
Al	0.296	0.028	0.268	ns
	$p < 0.0001$	$p < 0.009$	$p < 0.0001$	
Ca:Al ratio	0.206	ns	0.206	ns
	$p < 0.0001$		$p < 0.0001$	
Mg	0.092	ns	0.092	ns
	$p < 0.0001$		$p < 0.0001$	
K	0.179	0.016	0.163	ns
	$p < 0.0001$	$p < 0.0673$	$p < 0.0001$	
P	ns	ns	ns	ns
Fe	0.125	ns	ns	0.125
	$p < 0.0001$			$p < 0.0001$
Pb	0.049	ns	ns	0.049
	$p < 0.0032$			$p < 0.032$

ns = variance component not significant at $p \leq 0.150$.

appropriate (SAS, 1985) because it minimizes type I errors.

To best resolve the effects of thinning on soil properties, we then used ANOVA to compare the effect of thinning separately for each of the five sites with both thinned and control stands. In addition, we used forward selection, stepwise regression on the soil parameters to determine the proportional contribution of longitude, proportion of basal area removed during thinning in the 1960's, and the current

Table 5
Soil chemical conditions in control and experimentally thinned plots within five experimental forests. $N = 360$ for the pooled data and $N = 72$ for each experimental forest (except as otherwise noted), and standard errors of the means are given in parentheses. NO_3, NH_4 and Al were measured in 2 M KCl extracts and Ca, Mg, K, Fe, P and Pb in 1 M NH_4CH_2COOH. All parameters except pH are in mg/kg dry soil

Experimental forest	pH	NO_3	NH_4	TIN	PO_4	Ca	Mg
All five experimental forests pooled							
Control plots	4.37	0.41	1.38	1.79	1.36	172.3	40.4
	(0.03)	(0.04)	(0.06)	(0.08)	(0.03)	(18.5)	(3.7)
	****	****	*	****	****	****	****
Thinned plots	4.70	1.17	1.60	2.77	1.17	267.6	62.2
	(0.05)	(0.13)	(0.10)	(0.16)	(0.04)	(25.5)	(5.1)
Robinson (KY)							
Control plots	4.80	0.25	1.46	1.72	1.48	519.9	122.9
	(0.08)	(0.08)	(0.10)	(0.12)	(0.06)	(68.9)	(11.1)
	****	***	*	***	ns	ns	ns
Thinned plots	5.56	3.14	1.04	4.19	1.57	681.2	129.3
	(0.08)	(0.36)	(0.19)	(0.39)	(0.07)	(67.1)	(10.6)
Bald Rock (KY)							
Control plots	4.36	0.42	1.59	2.01	1.37	61.5	12.2
	(0.10)	(0.10)	(0.18)	(0.10)	(0.07)	(5.2)	(0.9)
	**	ns	ns	ns	****	****	****
Thinned plots	4.77	0.50	1.66	2.16	0.80	206.0	79.4
	(0.10)	(0.12)	(0.19)	(0.22)	(0.07)	(39.7)	(14.2)
McKee (KY)							
Control plots	4.30	1.01	1.58	2.60	1.32	70.2	17.4
	(0.04)	(0.10)	(0.11)	(0.16)	(0.07)	(3.9)	(1.1)
	****	***	***	***	ns	****	****
Thinned plots	4.56	1.55	2.56	4.11	1.16	205.7	42.1
	(0.05)	(0.20)	(0.29)	(0.31)	(0.09)	(30.2)	(5.2)
Mead (OH)							
Control plots	4.28	0.26	1.45	1.71	1.38	148.4	36.2
	(0.03)	(0.06)	(0.12)	(0.16)	(0.07)	(17.4)	(3.8)
	ns	*	ns	*	**	ns	ns
Thinned plots	4.37	0.62	1.68	2.30	1.06	144.5	41.8
	(0.05)	(0.18)	(0.15)	(0.22)	(0.07)	(31.3)	(5.7)
Raccoon (OH)							
Control plots	4.11	0.08	0.84	0.92	1.25	61.4	13.0
	(0.03)	(0.04)	(0.09)	(0.11)	(0.07)	(5.8)	(1.0)
	ns[a]	ns	ns	ns	ns	*	*
Thinned plots	4.23	0.04	1.05	1.10	1.27	100.6	18.6
	(0.06)	(0.02)	(0.16)	(0.16)	(0.09)	(22.2)	(3.0)

Table 5 (continued)

Experimental forest	K	Al	Ca:Al molar ratio	Fe	Pb
All five experimental forests pooled					
Control plots	68.7	186.0	6.4	0.54	0.24
	(1.8)	(6.7)	(2.2)	(0.03)	(0.03)
	****	****	****	ns	ns
Thinned plots	84.9	121.2	44.3	0.59	0.22
	(3.0)	(7.4)	(9.6)	(0.07)	(0.03)
				$N = 327$	$N = 189$
Robinson (KY)					
Control plots	91.0	85.8	30.8	0.34	0.18
	(4.0)	(13.5)	(10.5)	(0.04)	(0.05)
	****	***	****	ns	ns
Thinned plots	118.9	16.1	185.1	0.38	0.14
	(4.7)	(5.5)	(34.2)	(0.06)	(0.02)
				$N = 60$	$N = 34$
Bald Rock (KY)					
Control plots	61.2	152.7	0.3	0.87	0.40
	(4.1)	(6.7)	(0.1)	(0.10)	(0.14)
	*	**	*	ns	ns
Thinned plots	82.9	106.1	31.0	1.12	0.41
	(8.3)	(13.6)	(15.6)	(0.30)	(0.11)
				$N = 70$	$N = 33$
McKee (KY)					
Control plots	58.6	193.2	0.3	0.47	0.20
	(2.3)	(10.1)	(0.2)	(0.05)	(0.02)
	****	****	*	ns	ns[b]
Thinned plots	86.2	111.4	3.4	0.43	0.14
	(4.5)	(9.1)	(1.5)	(0.05)	(0.01)
				$N = 69$	$N = 35$
Mead (OH)					
Control plots	85.0	309.1	0.4	0.35	0.19
	(3.5)	(11.2)	(0.1)	(0.03)	(0.02)
	ns[c]	****	*	ns	ns
Thinned plots	75.0	201.7	1.3	0.38	0.22
	(3.7)	(17.4)	(0.6)	(0.04)	(0.02)
				$N = 58$	$N = 43$
Raccoon (OH)					
Control plots	47.9	189.2	0.2	0.65	0.24
	(1.8)	(8.9)	(0.1)	(0.05)	(0.13)
	*	ns	ns[d]	ns	ns
Thinned plots	61.4	170.8	0.6	0.54	0.13
	(6.4)	(8.6)	(0.3)	(0.04)	(0.02)
				$N = 70$	$N = 44$

Significance codes for differences between control and experimentally thinned plots are: **** $p < 0.0001$; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = difference not significant at $p < 0.05$.

[a] $p < 0.072$.
[b] $p < 0.068$.
[c] $p < 0.068$.
[d] $p < 0.095$.

basal area (as of 1992–93) to variation in soil chemical parameters. All data sets were tested for normality and homogeneity of variances prior to ANOVA; none required transformation prior to analysis.

The ANOVA model requires that all experimental material be relatively uniform at the beginning of the experiment and allocated among treatments randomly. The original establishment reports for the sets of plots we sampled suggest that the plots were chosen at random from a larger set of appropriate oak-dominated plots and that the plots were assigned appropriately to control vs. thinned treatments. The horizon descriptions, texture data, extensive discussions with the Forest Service personnel who established the experiments, and examination of the general notes on soil types in the original establishment reports suggest that the soils should have been relatively uniform among plots at the beginning of the experiment, and within an experimental forest there was consistency in parent material, slope position, aspect and age among plots. However, with no soil chemical data from the time of establishment, we cannot say with certainty that the soils did not differ between control plots and plots to be thinned prior to thinning.

3. Results

The two-way ANOVA revealed significant differences among experimental forests for all 12 soil properties and between thinned and control plots for nine of the soil properties (Table 2). Only Fe and Pb did not differ significantly between thinned and control plots. However, while the interaction between experimental forests and stand management was significant for all soil properties except Fe and Pb, there was clearly a failure of the difference between thinned and control plots to be consistent among all study sites. To best illustrate both the patterns of difference among experimental forests and the nature of the interaction with management, we analyzed the differences among forests with pooled samples from thinned and control plots, and then analyzed soil properties from each forest separately with thinning as the main effect.

3.1. Variations among experimental forests

Soil properties varied in three general patterns among experimental forests. First, there were patterns of variation that correlated well with longitude. Soil pH and soluble Al were significantly correlated with longitude (Fig. 1, Table 3), as was extractable PO_4 ($r = 0.74$, $p < 0.05$) (Table 3). Furthermore, interpolating the pH and Al concentration from similar sites in the Hoosier National Forest in Indiana (Boerner and LeBlanc, 1995) strengthened this relationship, especially for Al. Second, there were patterns typified by Ca, Mg and the molar Ca:Al ratio in which the soils from Kaskaskia and Robinson had significantly greater extractable levels than those from the other five sites (Table 3). Third, there were soil properties that decreased linearly from west to east (e.g., K and NO_3) or did not vary in any consistent manner (e.g., NH_4) between Kaskaskia and the two Ohio sites (Mead and Raccoon) but which were then significantly greater in soils at Fernow (Table 3).

3.2. Variations between thinned and control plots

Over the five sites with paired thinned and control plots, stepwise regression also revealed significant effects of thinning on soil pH, NO_3, TIN, Ca, Al, Ca:Al ratio, Mg and K. The proportion of variance explained by thinning varied from 9.2% for Mg to 60.5% for Ca (Table 4). In contrast, current basal area was significant only for NH_4, TIN, Fe and Pb, and accounted for $\geq 5.0\%$ of the variance for Fe only. Although longitude was significant for six soil parameters among these five experimental forests, the variance attributable to experimental thinning exceeded that attributable to longitude (Table 4). Thus, including aspects of the thinning treatments as main effects and restricting the data set to sets of paired control and thinned plots reduced the dependence of soil chemistry on longitude.

The ANOVA of soil parameters from that subset of five experimental forests revealed that the eight soil properties (pH, NO_3, NH_4, TIN, Ca, Mg, K and Ca:Al ratio) exhibited greater concentrations or greater values in thinned than in control plots (Table 5). In contrast, concentrations of PO_4 and Al were greater in control than in thinned plots. Fe and Pb did not vary significantly between thinned and control plots.

There was a range of differences between control and thinned plots in the soils from the three experimental forests in Kentucky. At Robinson, NH_4 and Al concentrations were greater in soils from control plots, whereas pH, NO_3, TIN, K and Ca:Al ratio were all greater in thinned plots (Table 5). Similarly, at Bald Rock, pH, Ca, Mg, K and the Ca:Al ratio were all greater in thinned plots, and PO_4 and Al were greater in the control plots (Table 5). At McKee, thinned plots had greater pH, NO_3, NH_4, TIN, Ca, Mg, K and Ca:Al ratio, and only Al was greater in control plots (Table 5).

There were fewer significant differences between soils from thinned than control plots in the two Ohio forests. At Mead, NO_3, TIN and PO_4 were significantly more available in thinned plots, whereas Al was more available in control plots (Table 5). At Raccoon, Ca, Mg and K were more available in the thinned plots (Table 5). However, there were differences between soils at $0.10 > p > 0.05$ for the Ca:Al ratio at both Mead and Raccoon, pH at Raccoon and K at Mead (Table 5). Given the high degree of random variability in field soils from natural ecosystems, differences at $p < 0.10$ should probably be considered strongly suggestive if not statistically significant.

Overall, at least four of the five experimental forests soils from the thinned plots had greater pH, K and Ca:Al ratio than soils from control plots, and in three of the five experimental forests, soils from the thinned plots had significantly greater availability of NO_3, TIN and Mg (Table 6). In contrast, in four experimental forests, Al was more available in control than in thinned plots (Table 6). When data from the five forests were pooled, it was apparent that soils from the thinned plots had significantly greater pH, NH_4, TIN, Ca, Mg, K and Ca:Al ratio and significantly lower Al and PO_4 than soils from the control.

In the absence of pretreatment data, we used a bootstrap approach to help clarify whether differences among plots in 1993 might have been by random chance rather than due to the effects of thinning. We iteratively subdivided the six control plots from the Kaskaskia Experimental Forest into the 12 possible combinations of three control and three treatment plots, then compared the magnitude of differences in the chemical characteristics of soil among those 12 sets of control and thinned plots by ANOVA.

Among the 12 sets of virtual treatment and control plots at Kaskaskia, none differed significantly in pH or PO_4 and only one pair differed significantly in NO_3 (Table 7). In contrast, the frequency of significant differences in these three soil properties among actual thinned and control plots in five experimental forests were 80%, 40% and 60%, respectively. For the five soil parameters examined in this manner, the average mean frequency of significant differences was 64% for the five experimental forests and 15% for the 12 randomly derived sets of plots in Kaskaskia (Table 7).

Table 6
Summary of soil parameters which differed significantly between thinned and control plots in five experimental forests. Differences significant at $0.10 > p > 0.05$ are indicated in parentheses. Experimental forests are ordered from west to east

Experimental forest	Thinned > Control	Control > Thinned
All sites pooled	pH, NO_3, NH_4, TIN, Ca, Mg, K, Ca:Al	Al, PO_4
Robinson (KY)	pH, NO_3, TIN, K, Ca:Al	Al, NH_4
Bald Rock (KY)	pH, Ca, Mg, K, Ca:Al	Al, PO_4
McKee (KY)	pH, NO_3, NH_4, TIN, Ca, Mg, K, Ca:Al	Al, (Pb)
Mead (OH)	NO_3, TIN, Ca:Al	Al, PO_4, (K)
Raccoon (OH)	(pH), Ca, Mg, K, (Ca:Al)	–

Table 7
Comparison of the frequency of significant differences in soil properties (at $p < 0.10$) between thinned and control plots in five experimental forest and the frequency of such differences in 12 randomly derived sets of plots from the Kaskaskia Experimental Forest

Soil property	Frequency in five experimental forests (%)	Frequency in twelve set of control plots (%)
pH	80	0
NO_3	60	8
P	40	0
Ca	60	42
Al	80	25
Mean Frequency	64	15

4. Discussion

The A-horizon pH and extractable Al in soils of these seven experimental forests decreased linearly from west to east, along the historical and continuing gradient of atmospheric deposition. Although this pattern has been demonstrated and/or assumed in areas that are highly susceptible to acidification, such as ridgetops and high elevation sites (e.g., Bondietti and McLaughlin, 1992), it was striking even in these mesic and presumably acidification-resistant microsites.

Several other parameters, especially inorganic N forms, also decreased linearly from west to east from Illinois to Ohio, but were higher in soils from Fernow, our easternmost site. This pattern of variation was also consistent with that reported for total N mineralization in aerobic incubations (Boerner and Sutherland, 1995). The Fernow may not have, in retrospect, been as good a fit for our study as the other sites as it is 300–600 m higher in elevation, and has the greatest total atmospheric deposition (NADP/NTN, 1992, 1993). Perhaps more importantly, plots near our sampling sites at Fernow had received experimental additions of $(NH_4)_2SO_4$ applied aerially for several years prior to our sampling. It is possible that drifting $(NH_4)_2SO_4$ dust from these experiments may have affected the N status of our sampling sites.

There were also patterns of variation in soil properties that were not related to longitude, which seemed to be more related to differences in the parent materials from which the soils were derived. Soils at Kaskaskia and Robinson had significantly greater Ca, Mg and Ca:Al ratio than those from the other sites. We believe that the presence of some loess at Kaskaskia and limy inclusions in the sandstone/siltstone at Robinson were responsible for these patterns. Thus, longitudinal patterns related to normal processes of weathering and a long history of atmospheric deposition may still be obscured by differences in parent material (as in Ca and Mg) and by confounding experimental treatments (as at Fernow).

Perhaps the most intriguing result of this study was the finding that the soils of experimentally thinned plots tended to be higher in pH, inorganic N, Ca, Ca:Al ratio and Mg, whereas the control sites had lower pH and greater Al availability. In other words, the soils of the control sites had become more heavily weathered, leached and acidified than the soils of plots from which biomass had been removed more than 30 yr earlier. If these differences are due to the initial and/or lingering effects of the experimental treatments, and total precipitation and atmospheric deposition were similar among plots within a forest, then changes in the rates and patterns of nutrient cycling with the potential to affect available nutrient pool sizes for decades must have resulted from these treatments.

We suggest that the thinning treatments lowered total stand nutrient uptake rates for some time, and that this effectively increased nutrient availability, at least in relation to microbial and plant demand. In an environment with greater relative nutrient availability, the leaf litter produced has greater nutrient content, lower structural C content and lower lignin content (Boerner, 1984a,b). Such detritus turns over more rapidly than that from trees growing on nutrient-poor sites. Thus, greater soil-available pools are maintained than would be the case at sites with lower nutrient availability (e.g., control plots) where poorer-quality litter with greater lignin and polyphenolic content ties up nutrients and results in poor-quality detritus that is slow to turn over. Similarly, the increased soil surface temperatures and moisture levels present during the first years after thinning, possibly coupled with increased nitrification rates resulting from lowered competition between plants and microbes for NH_4, may have resulted in increased releases of base cations through weathering and mineralization. This was demonstrated following whole-tree harvests in New England (Hornbeck, 1992).

Although studies of nutrient dynamics immediately following clearcutting are common (e.g., Likens et al., 1969; Matson and Vitousek, 1981), there are few parallel, long-term studies of the effects of thinning on soil nutrient dynamics with which to compare or verify our results. Krug and Frink (1983) cited unpublished data from Connecticut forests suggesting that a reduction in oak basal area from 30.2 m^2/ha to 4.6 m^2/ha resulted in an increase in forest floor pH from 3.8 to 4.2, and Hornbeck (1992) reported an increase in forest floor and mineral soil pH of 0.2 to 0.4 pH units over 3 yr following whole-tree harvest. As our regression models suggest that the proportion of basal area removed explained more of the variance in soil properties among sites and treatments than either the rate of regrowth or longitude, more intensive studies are needed to determine the relationship between the degree of biomass removal during harvest and subsequent, long-term changes in soil acidification.

Alternatively, we cannot rule out the possibility that the differences between thinned and control plots observed in 1993 reflect pretreatment differences that existed in 1960, and not the effects of thinning. We attempted to minimize this possibility by holding parent material, slope, aspect, age and composition constant among plots within an experimental forest, and by performing bootstrap analyses among 12 sets of virtual plots in Kaskaskia. Although we believe that those two steps reduce the possibility that pretreatment differences are responsible for the consistent pattern of variation between control and thinned plots observed over five different experimental forests, we have been unable to locate pretreatment soil data for verification. We urge other researchers with access to similar long-term experiments to repeat our study to determine the generality of these patterns.

Of particular concern in considering the broader implications of this data set was the pattern of differences in soluble Al and Ca:Al molar ratio among sites and between control and thinned plots. A variety of studies has demonstrated significant impacts of Ca:Al ratios < 5 on growth and foliar nutrient concentrations of a range of tree species (Cronan and Grigal, 1995). For example, Matzner (1989) observed that symptoms of Mg deficiency began to develop in European spruce forests when the Ca:Al ratio decreased to below 0.5, and Huttermann and Ulrich (1984) concluded that the Ca:Al ratio was the best predictor of decline of spruce forests in Norway. For the tree species common in our study sites, impacts on growth and nutrient concentrations develop when the Ca:Al ratio in the soil decreased to below 0.4–4.5, depending on the species (Cronan and Grigal, 1995).

Overall and in five of our seven study areas, the Ca:Al ratio was significantly lower for soils in control than in thinned plots. At Bald Rock and McKee, the Ca:Al ratio met or exceeded the threshold for physiological damage in thinned plots but not in control plots. Furthermore, at Raccoon and Mead, the Ca:Al ratio in both control and thinned plots was < 1.0, the critical threshold for forest decline established by Sverdrup and Warfvinge (1993). These data suggest that chronic changes in the Ca:Al ratio of forest soils due to acidic precipitation and forest growth, such as those described by Cronan and Schofield (1990) in a survey of North American and European forests, may be reaching the point at which significant growth impacts can be anticipated.

Various forest tree species differ in sensitivity to Al and the threshold Ca:Al ratio at which they begin to show growth declines (Cronan and Grigal, 1995), and forests with different levels of total ecosystem N and inorganic N pool sizes often differ in species composition (Vogt et al., 1991). Thus, it is difficult to predict how these changes might affect future forest composition and growth. However, studies suggest that vesicular arbuscular-mycorrhizae can significantly increase the tolerance of host plants to increases in soluble Al and lowered the Ca:Al ratio (e.g., Koslowsky and Boerner, 1989), and suggest that the ectomycorrhizal fungi are not able to confer such Al tolerance to their hosts (e.g., Hentschel et al., 1993). Also, both survey data and experimental studies have demonstrated a differentially negative impact of chronic N deposition/addition on ectomycorrhizal fungi and their hosts (Arnolds, 1991; Jansen, 1991). Thus, differences in sensitivity of ectomycorrhizae and their hosts to decreasing Ca:Al ratio and chronic N deposition may be a significant underlying factor in the observed shift in dominance from ectomycorrhizal to arbuscular mycorrhizal tree species in forests of eastern North America.

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