# Chapter 5

# Soil and Forest Floor Characteristics

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## Abstract

The soils of the four study areas in southern Ohio were dominated by silt loams derived from sandstones and shales. The soils at Bluegrass Ridge (BR) had significantly more clay and sand and significantly less silt than soils of the other study areas. Total inorganic N (TIN) and available $NH_4$ were greatest in soils from Watch Rock (WR) and least at Young's Branch (YB). TIN, $NH_4$, and $NO_3$ availability varied directly with Integrated Moisture Index (IMI). Soil pH, $PO_4$, Ca, Mg, and molar Ca:Al ratio also varied among sites; soils from Arch Rock (AR) had the lowest pH, Ca, Mg, and Ca:Al ratio while those from BR had the highest. Al and pH varied with IMI as soils from xeric plots had the lowest pH and the highest soluble Al levels. The availability of $PO_4$, Ca, and Mg and the Ca:Al ratio were lower in soils from xeric plots than from intermediate and mesic plots. Unconsolidated litter mass averaged 438 g/m$^2$ and did not differ significantly among treatment units or IMI classes. Litter mass was greatest at YB, averaging 527 g/m$^2$. Detrended Correspondence Analysis indicated that a strong pH/mineral availability gradient was the primary factor that influenced soil chemistry among the study 108 plots. Mesic plots from BR and WR separated in the ordination from the remainder of the sample plots, suggesting that these plots may not be as useful as the remaining plots for detecting subsequent fire effects on soils and belowground processes.

## Introduction

The physiography and parent materials within the Unglaciated Allegheny Plateau of southern Ohio control the physiochemical characteristics and rates and patterns of nutrient cycling in soil of forested watersheds when major disturbances are rare (Finney et al. 1962; Boerner 1985). Portions of some watersheds in this region are underlain by limestone. These areas generate soils that are significantly higher in pH and base cations than those underlain by the region's widespread and relatively acidic sandstones, shales, and coals. Because forest productivity often varies as a function of soil nutrient availability and species distributions often are correlated with the presence or absence of limestone, a significant proportion of the heterogeneity observed in the forested landscape of southern Ohio can be attributed to occasional limestone outcrops (see Chapter 4).

In areas underlain by relatively acidic sandstones and shales, as is the case for most of our 108 study plots, differences in microclimate among slope positions and aspects generate differences in soil development, horizon depth, accumulation of organic matter, and rates of decomposition. This results in greater soil-horizon development and nutrient availability and lower decomposition rates on south- and west-facing slopes than on the more mesic north- and east-facing slopes (Finney et al. 1962; Hutchins et al. 1976; Boerner 1984). As a result, N mineralization rate and nitrification, the processes that convert organic N into forms available for tree use, also are greater on mesic slopes (Plymale et al. 1987).

Despite small differences in the annual rate of leaf, branch, and litter deposition among stands within watersheds, patterns of leaf litter redistribution following litterfall result in the ridgetops and drier south- and west-facing slopes serving as net donors of organic matter and nutrients to the more mesic north- and east-facing slopes (Welbourn et al. 1981; Boerner and Kooser 1989). Thus, nutrients taken up from the soil by trees on the drier slopes and ridgetops may be deposited in detritus and recycled on mesic slopes (Boerner and Kooser 1989). Gradients of soil-nutrient availability and nutrient cycling rates are thus maintained in these physiographically diverse watersheds by a combination of geological, microclimatological and ecological processes.

Leaf litter also plays an important role in plant communities (Facelli and Pickett 1991). By serving as a mechanical barrier, leaf litter can hinder the emergence of tree seedlings (Myster 1994) and forbs (Bosy and Reader 1995), which, in turn, reduces species richness (Beatty and Sholes 1988).

In this chapter we document variations in physiochemical characteristics of the soil and the forest floor in the four study areas prior to the reintroduction of surface fires. Specifically, we characterize the current ecological status of these soils and draw inferences concerning variations in soil physiochemical status among study areas and treatment units in relation to aspect- and elevation-driven differences in microclimate.

# Methods

## Study Areas and Experimental Design

The study areas and experimental design are described in detail in Chapter 1. Here a brief overview is provided. The four 75-90 ha study areas are located in Vinton County (Arch Rock and Watch Rock) and Lawrence County (Young's Branch and Bluegrass Ridge). The study areas are within in the Southern Unglaciated Allegheny Plateau, which is characterized by high hills, sharp ridges, and narrow valleys. Sandstones and shales are principle bedrocks. Forests are oak-dominated and the current overstory originated in the late-1800s, after the cessation of clearcutting for the charcoal iron industry.

In each study area, three prescribed fire treatments were established, a control unit (CONT), an infrequent burn unit (INFR), and a frequent burn unit (FREQ). To account for variation in soil moisture and vegetation, a GIS-derived integrated moisture index (IMI) was applied across the dissected landscapes of the study areas (Chapter 3). From the calculated IMI scores, each 30 x 30 m pixel was assigned to one of three soil moisture classes: xeric, intermediate, or mesic. Thus to examine the effects of prescribed fire and account for environmental heterogeneity, a split-plot experimental design was established. The four study areas are replicate blocks, fire treatment units are whole plots, and IMI classes are subplots. The 50 x 25 m vegetation plots (N= 108 total) were established as pseudoreplicates in each IMI class within each fire treatment unit (Chapter 1).

## Field and Laboratory Methods

In October and November 1994, bulk soil samples were obtained for initial soil characterization. Two A-horizon samples of approximately 1 kg were obtained from randomly selected points 1 to 2 m outside the upper and lower boundaries of each vegetation plot. The bulk soil samples were air dried for approximately 14 days and then passed through a 6-mm sieve to remove roots, wood fragments, and large gravel.

Soil texture was determined on 40-g (dry mass) subsamples from each sieved sample by the hydrometer method; sodium hexametaphosphate was used to disperse carbonates. Soil pH was determined in 1:5 soil: 0.01 M $CaCl_2$ slurries. Subsamples of 10 g were extracted with 2 M KCl for subsequent analysis of $NO_3$, $NH_4$, and Al, and with 1 M $NH_4OAC$ for subsequent analysis of Ca, Mg by atomic absorption, and $PO_4$ by the stannous chloride method. All methods follow Page et al. (1982). Total inorganic N (TIN) was calculated as the sum of $NO_3$ and $NH_4$; the Ca:Al ratio was expressed on a molar basis.

In 1996, six leaf litter samples were collected per vegetation plot 1 m from each plot corner in March and April. A square metal frame (0.0225 $m^2$) with a cutting edge was used to obtain the samples. Because the long-term goal is to examine litter dynamics in response to prescribed fire, not all forest floor layers were collected. The entire L layer was collected, as was litter larger than 2 by 2 cm in the F layer. Smaller pieces in the F-layer, litter that was matted together (partially decomposed), and in the H layer were not collected as these components were not expected to burn in a prescribed fire. Twigs less than 0.5 cm in diameter were collected, but larger twigs, pieces of bark, and nuts were not. The samples were placed in plastic bags, transferred to paper bags and placed in a drying oven within 5 days, and dried at 70°C for 48 hr prior to weighing.

## Data Analysis

Percentages of sand, silt, and clay, pH, minerals, litter mass, and inorganic N forms were compared among study areas, treatment units within study areas, and IMI classes within areas by analysis of variance (ANOVA) for a split plot, mixed-factor design with maximum likelihood estimators (Proc Mixed, ML option) using SAS (1994). All data were tested for normality prior to ANOVA, and none required transformation to fit the assumptions of the analysis. Detrended Correspondence Analysis (DCA; PC-Ord 3.0) was used to compare the soils of all 108 vegetation plots using 12 physical and chemical variables simultaneously (Hill and Gauch 1980).

# Results

Silt loams dominated the bulk soil samples: 79 percent of the 216 samples analyzed were silt loams. Loams accounted for 14 percent and clay loams 7 percent. A single sample of sandy clay loam was collected at BR. Textural diversity was low at all study areas except BR. In the other study areas, nearly 85 percent of all soil samples were silt loams, while the soils at BR were distributed more evenly among textural

**Table 1.-Results of mixed-model ANOVA for soil characteristcs (ns=not significant).**

| Item | Study area | Unit | IMI class | Unit* IMI Class |
|---|---|---|---|---|
| Sand | p<0.0008 | ns | p<0.0209 | ns |
| Silt | p<0.0011 | ns | p<0.0124 | ns |
| Clay | p<0.0033 | ns | p<0.0252 | ns |
| PH | p<0.0056 | ns | p<0.0001 | ns |
| $NH_4$ | p<0.0001 | ns | p<0.0001 | ns |
| $NO_3$ | ns | ns | p<0.0054 | ns |
| TIN | p<0.0425 | ns | p<0.0001 | ns |
| $PO_4$ | p<0.0001 | ns | p<0.0001 | ns |
| Ca | p<0.0001 | ns | p<0.0001 | ns |
| Mg | p<0.0001 | p<0.03 | p<0.0001 | ns |
| Al | ns | ns | p<0.0001 | ns |
| Ca:Al ratio | i<0.0051 | ns | p<0.0064 | ns |
| Litter mass | | ns | ns | ns |

**Table 2.-Percent sand, silt, and clay in A-horizon soils of the four study areas and relative to IMI class (standard errors in parentheses).**

| | | | | | IMI Class | | |
|---|---|---|---|---|---|---|---|
| Item | Arch Rock | Watch Rock | Bluegrass Ridge | Young's Branch | Xeric | Intermediate | Mesic |
| Sand | 25.4a (0.8) | 25.6a (0.6) | 33.6b (0.8) | 27.0a (0.9) | 28.2b (0.9) | 29.7b (0.7) | 25.7a (0.7) |
| Silt | 61.9b (1.0) | 61.9b (1.0) | 50.6a (1.2) | 59.7b (1.3) | 57.9a (1.3) | 55.9a (1.1) | 61.8b (0.9) |
| Clay | 12.6a (0.3) | 12.6a (0.4) | 15.9b (0.5) | 13.3a (0.5) | 13.9a (0.4) | 14.4b (0.4) | 12.5a (0.3) |

Note: Means followed by the same letter not significantly different (p>0.05).

classes (46 percent silt loams, 37 percent loams, 15 percent clay loams, and 2 percent sandy clay loams).

The proportions of sand, silt, and clay varied significantly among study areas (Table 1). Soils from BR had significantly more sand and clay and significantly less silt than soils from the other study areas (Table 2). There were no significant differences in textural classes among treatment units, but there were significant differences in soil textural classes among IMI classes (Table 1). Mesic vegetation plots had significantly less sand and more silt than intermediate and xeric plots. Intermediate plots had the most clay content (Table 2).

There were significant differences both among study areas and IMI classes in extractable $NH_4$ and TIN while extractable $NO_3$ differed significantly only among IMI classes (Table 1). $NH_4$ concentrations were greatest in soils from WR and lowest in soils from YB (Table 3). TIN also was greatest in soils from WR exceeding TIN in soils of the other study areas by an average of 69 percent.

Concentrations of $NO_3$ and $NH_4$ were significantly lower in soils from the xeric plots than in soils from intermediate and mesic plots (Table 3). TIN availability increased from xeric to intermediate to mesic plots; mean TIN concentrations differed significantly among all three IMI classes.

Soil pH, extractable $PO_4$, Ca, Mg, and molar Ca:Al ratio all differed significantly among both study areas and IMI classes; extractable Al differed significantly only among IMI classes (Table 1). Soils from AR had the lowest mean pH and those from BR had the highest (Table 3). Soils from YB and BR had significantly greater concentrations of extractable $PO_4$ than soils from AR and WR (Table 3).

Soils from BR had greater extractable concentrations/ratios of Ca, Mg, and molar Ca:Al than those from the other study areas (Table 3). Variations in Ca availability

**Table 3.-Chemical properties of A-horizon soils of the four study areas and relative to IMI class (standard errors in parentheses).**

| Item[a] | Arch Rock | Watch Rock | Bluegrass Ridge | Young's Branch | IMI class Xeric | Intermediate | Mesic |
|---|---|---|---|---|---|---|---|
| $NH_4$ | 11.59b (1.04) | 15.07a (1.51) | 11.85b (0.75) | 8.20c (0.70) | 6.96a (0.56) | 12.92b (0.78) | 14.78b (1.12) |
| $NO_3$ | 1.42a (0.42) | 8.07a (2.27) | 2.57a (0.90) | 5.37a (1.36) | 0.50b (0.14) | 3.49b (0.86) | 8.85a (1.77) |
| TIN | 13.01a (1.29) | 23.14b (2.83) | 14.42a (1.23) | 13.57a (1.86) | 7.47c (0.61) | 16.41b (1.25) | 23.63a (2.17) |
| pH | 3.92a (0.06) | 4.13ab (0.12) | 4.43c (0.09) | 4.34bc (0.12) | 3.75b (0.07) | 4.33a (0.08) | 4.49a (0.09) |
| $PO_4$ | 0.13b (0.01) | 0.10b (0.01) | 0.22a (0.01) | 0.25a (0.02) | 0.12a (0.01) | 0.21b (0.02) | 0.19b (0.01) |
| Ca | 249.0b (38.2) | 408.5b (79.0) | 2425.2a (268.6) | 593.0b (81.2) | 461.9a (136.1) | 1305.8b (198.6) | 943.7b (132.1) |
| Mg | 61.6b (8.9) | 84.1b (12.8) | 319.1a (25.7) | 71.9b (7.8) | 76.8a (14.6) | 185.5b (21.5) | 134.2b (15.7) |
| Al | 231.8a (21.5) | 220.9a (23.9) | 172.9a (31.0) | 174.6a (23.5) | 358.7a (21.8) | 154.9b (17.7) | 100.3c (12.9) |
| Ca:Al Ratio | 24.4a (13.1) | 134.8ab (44.7) | 359.2c (96.9) | 226.3b (89.5) | 67.5b (41.0) | 235.8a (58.1) | 238.3a (74.9) |
| Litter mass | 414.2 (22.9) | 382.5 (17.0) | 421.2 (14.9) | 527.9 (30.0) | 442.2a (35.2) | 439.7a (34.9) | 425.2a (35.1) |

[a] Except for pH and CA:Al ratio, all items are in mg/kg/soil.

were more important than variations in Al in determining inter-area differences in Ca:Al ratio.

There were two general patterns of variation in pH and mineral availability among IMI classes. Al and pH varied linearly with IMI class. Soils from xeric plots had the greatest Al concentrations and the lowest pH (Table 3). By contrast, for $PO_4$, Ca, Mg, and Ca:Al ratio, availability/ratio was lower in soils from xeric plots than in soils from intermediate and mesic plots. However, levels did not differ significantly between soils from intermediate and mesic plots (Table 3).

Unconsolidated leaf litter was predominantly from oaks, which dominated the overstory in most plots (Chapter 9). Litter mass averaged 437 g/m$^2$ per plot. There were no significant differences in litter mass among IMI classes; litter mass averaged 442, 440, and 425 g/m$^2$ on xeric, intermediate, and mesic plots, respectively (Table 3). Although there was substantial variation in mean litter mass among units (239 to 677 g/m$^2$; Appendix), differences were not significant by treatment (Table 1). YB had the greatest litter mass, averaging 528 g/m$^2$, while litter mass at the other study areas averaged 383 to 421 g/m$^2$.

## Detrended Correspondence Analysis

We used DCA to compare all soil variables in all soil samples simultaneously. DCA arrayed the samples in two-dimensional space such that the distances between the points representing the various samples were proportional to the degree of overall physiochemical similarity. We performed this analysis to determine similarities among soils of the 108 vegetation plots when all of the properties we measured were compared simultaneously.

DCA spread out the vegetation plots along a first axis that accounted for 63.5 percent of the summed eigenvalues of the ordination (Fig. 1). The second axis accounted for an additional 29.2 percent of the summed eigenvalues, but produced significant spread of points only at the upper end of axis one. Thus, on the basis of soil chemical and textural properties, DCA arrayed the vegetation plots in a triangular cloud.

When the ordination points corresponding to vegetation plots were displayed by study area, it was apparent that the ordination had separated the plots from AR and WR at the lower end of axis 1 from the BR and YB plots at the upper end. Similarly, when the sample points were labeled by IMI class, it was clear that the dry plots clustered at the lower end of axis 1, and the intermediate and mesic plots separated along axis 2 at the upper end of axis 1 (Fig. 1).

Axis 1 scores were strongly, positively correlated with soil pH, inorganic N forms, Ca, Mg, and Ca:Al ratio, and strongly, negatively correlated with available Al (Table 4). Thus, the AR and WR xeric plots at the lower end of axis 1 were predominantly those with high Al, low pH, and low nutrient availability, whereas the more nutrient rich, less acidified soils from the BR and YB intermediate and mesic plots were at the upper end of axis 1.

Axis 2 scores were positively correlated with IMI and available N and negatively correlated with pH and mineral nutrient availability (Table 4). Thus, the plots arrayed at the upper end of axis 2, particularly those from mesic plots at YB and WR, represented the moistest plots and those with the greatest N availability. Those arrayed lower on axis 2 represented intermediate plots, primarily at BR, with high mineral nutrient availability.

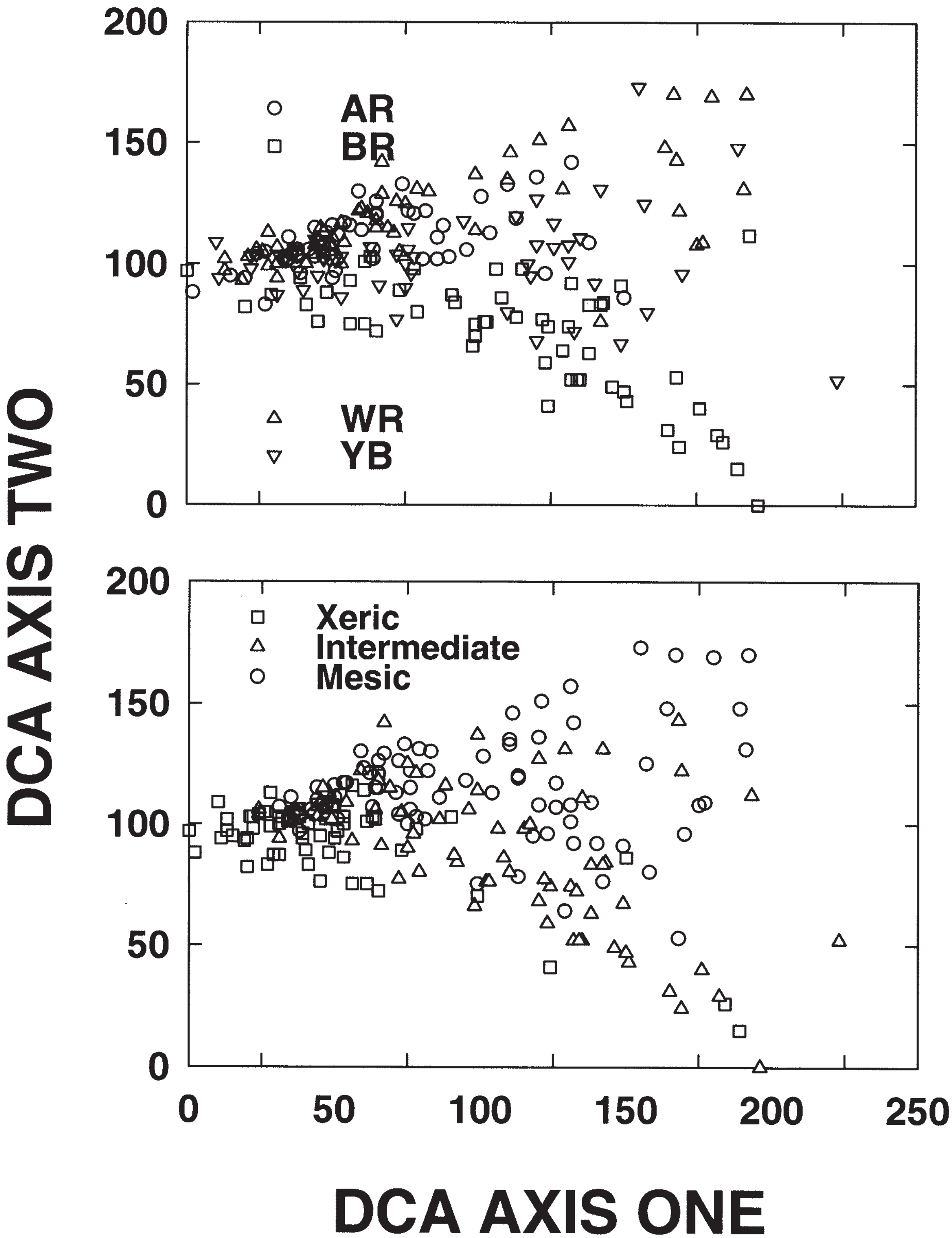


Figure 1.—Detrended Correspondence Analysis ordination of soils from 108 vegetation plots arrayed on the basis of study area (top) and IMI class (bottom).

**Table 4.-Pearson Product-Moment correlations between soil factors and DCA ordination axis scores (only correlations significant at $p \leq 0.05$ listed).**

| Item | Axis 1 | Axis 2 |
|---|---|---|
| pH | 0.864 | -0.181 |
| $PO_4$ | 0.514 | -0.304 |
| $NH_4$ | 0.424 | 0.338 |
| $NO_3$ | 0.609 | 0.391 |
| TIN | 0.677 | 0.471 |
| Ca | 0.723 | -0.675 |
| Mg | 0.703 | -0.635 |
| Al | -0.841 | ns |
| Ca:Al | 0.638 | -0.419 |
| Sand (%) | ns | -0.550 |
| Clay (%) | ns | -0.520 |
| IMI | 0.405 | 0.315 |

## Discussion

Most of the soils of the four study areas can be characterized as silt loams of colluvial and residual origin with relatively low pH and nutrient availability. However, we also found some vegetation plots with significantly greater pH, Ca, and Mg availability, particularly at BR. These plots probably reflect the influence of the scattered, discontinuous limestone strata that are found within the sandstone and shale matrix of the region (Chapter 4).

The influences of topography, aspect, and slope angle/shape on soil chemical properties were integrated in this study through the use of the IMI; pH and nutrient availability were lower and soluble Al higher in the soils on the driest vegetation plots. Several chemical parameters (e.g., TIN, pH, Al) varied linearly with IMI class, whereas others were similar in soils from intermediate and mesic plots. The texture, chemical properties, and intrawatershed variations of the soils of the study areas generally were consistent with and representative of those of a larger area of the Unglaciated Appalachian plateau of Ohio and Kentucky (Finney et al. 1962; Hutchins et al. 1976; Boerner 1984, 1985).

The inorganic N:P ratio in the soils from the study areas ranged from about 60:1 at BR, YB, and AR to 240:1 at WR. $NO_3$ accounted for 11 to 18 percent of TIN at AR and BR versus 35 to 40 percent at WR and YB. Such significant concentrations of $NO_3$ typically accumulate in forest soils when the supply of inorganic N from mineralization plus deposition exceeds the uptake capacity of microbes and plants (van Miegrot et al. 1992). These data suggest that the forests of southern Ohio have become strongly enriched in N due to fire suppression and atmospheric deposition (NADP/NTN 1992, 1993), and may no longer be N limited.

Mean Ca:Al molar ratios for the study areas ranged from 24:1 at AR to 360:1 at BR. However, in the driest vegetation plots at AR and WR, the Ca:Al ratio was commonly below 1.0. Several studies of forest decline have demonstrated significant impacts on growth and foliar nutrient concentrations for a range of tree species when the Ca:Al molar ratio drops below 5.0 (Cronan and Grigal 1995). Matzner (1989) observed nutrient deficiencies developing in European conifer stands when the Ca:Al ratio dropped to 5.0 or below, and Huttermann and Ulrich (1984) concluded that Ca:Al ratio was the best available predictor for forest decline in Scandinavian conifer forests. Additional research is needed to determine whether tree growth and/or nutrient dynamics are being affected by the existing Ca:Al balance in the soils of the study areas, and how repeated burning might cause those ratios to shift.

Leaf litter was distributed evenly across the landscapes of the study areas. Likewise, tree basal area did not differ significantly among treatments or IMI classes (Chapter 9). However, large standard deviations indicate high inter-plot variability unrelated to treatment units and IMI classes. This variability might be related to subtle microtopographic variations and litter redistribution (Boerner and Kooser 1989). YB had more litter, indicating higher litterfall and/or slower rates of litter decomposition. Mean forest-floor litter mass was about 1.5 fold greater than annual litterfall in oak forests of similar age in Hocking County, Ohio (Boerner and Kooser 1989). This finding suggests that a portion of litterfall remains unconsolidated into the F and H layers each year. The baseline data presented here will be useful in determining the dynamics of litter in response to prescribed burning.

DCA ordination identified a large cluster of sample plots with similar soil characteristics. These included most of the vegetations plots at AR and YB and a subset of those at WR and BR. The use of plots with similar soil characteristics will aid in detecting subtle fire effects, particularly in relation to IMI. The ordination also identified a smaller set of high N plots at WR and high Ca and N plots at BR as unique. This subset will be particularly useful in evaluating the influence of variations in underlying edaphic properties on the response of vegetation and ecosystem processes to fire.

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## Literature Cited


Beatty, S. W.; Sholes, O. D. V. 1988. **Leaf litter effect on plant species composition of deciduous forest treefall pits.** Canadian Journal of Forest Research. 18: 553-559.

Boerner, R. E. J. 1984. **Nutrient fluxes in litterfall and decomposition in four forests along a gradient of soil fertility in southern Ohio.** Canadian Journal of Forest Research. 14: 794-802.

Boerner, R. E. J. 1985. **Interrelations among soil nutrient availability, N and P cycling, and N and P use efficiency in four hardwood forest stands.** In: Dawson, J. P.; Majerus, K. A., eds. Proceedings of the fifth central hardwood forest conference, 1985 April 15-17; Urbana, IL. Urbana-Champaign, IL: University of Illinois: 125-137.

Boerner, R. E. J.; Kooser, J. G. 1989. **Leaf litter redistribution among forest patches within an Allegheny Plateau watershed.** Landscape Ecology. 2: 81-92.

Bosy, J. L; Reader, R. J. 1995. **Mechanisms underlying the suppression of forb seedling emergence by grass *Poa pratensis* litter.** Functional Ecology. 9: 635-639.

Cronan, C. S.; Grigal, D. F. 1995. **Use of calcium/ aluminum ratios as indicators of stress in forest ecosystems.** Journal of Environmental Quality. 24: 209-226.

Facelli, J. M.; Pickett, S. T. A. 1991. **Plant litter: its dynamics and effects on plant community structure.** Botanical Review. 57(1): 1-32.

Finney, H. R.; Holowaychuk, N.; Hiddleson, M. R. 1962. **The influence of microclimate on the morphology of certain soils of the Allegheny Plateau of Ohio.** Soil Science Society of America Proceedings. 26: 287-292.

Hill, M. O.; Gauch, H. G. 1980. **Detrended correspondence analysis: an improved ordination technique.** Vegetatio. 42: 47-59.

Hutchins, R. B.; Blevins, R. L.; Hill, J. D.; White, E. H. 1976. **Influence of soils and microclimate on vegetation of forested slopes in eastern Kentucky.** Soil Science. 121: 234-241.

Huttermann, A.; Ulrich, B. 1984. **Solid phase-solution-root interactions in soils subjected to acid deposition.** Philosophical Transactions of the Royal Society of London (Ser. B). 305: 353-368.

Matzner, E. 1989. **Acidic precipitation: case study Sollinger.** In: Adriano, D. C.; Havas, M., eds. Acidic precipitation. Vol. 1. New York: Springer-Verlag: 39-84.

Myster, R. W. 1994. **Contrasting litter effects on old field tree germination and emergence.** Vegetatio. 114: 169-174.

National Atmospheric Deposition Program/National Trends Network. 1992. **NADP/NTN annual data summary: precipitation chemistry in the United States.** Fort Collins, CO: National Atmospheric Deposition Program/National Trends Network. http://nadp.nrel.colostate.edu/NADP.

National Atmospheric Deposition Program/National Trends Network. 1993. **NADP/NTN annual data summary: precipitation chemistry in the United States.** Fort Collins, CO: National Atmospheric Deposition Program/National Trends Network. http://nadp.nrel.colostate.edu/NADP.

Page, A. L.; Miller, R. H.; Keeney, D. R., eds. 1982. **Methods of soil analysis. Part 2. Chemical and microbiological properties.** Madison, WI: American Society for Agronomy. 1,159 p.

Plymale, A. E.; Boerner, R. E. J.; Logan, T. J. 1987. **Relative nitrogen mineralization and nitrification in soils of two contrasting hardwood forests: effects of site microclimate and initial soil chemistry.** Forest Ecology and Management. 21: 21-36.

SAS Institute, Inc. 1994. **Statistical analysis system. User's guide: statistics.** Cary, NC: SAS Institute, Inc. 956 p.

van Miegrot, H.; Cole, D. W.; Foster, N. W. 1992. **Nitrogen distribution and cycling.** In: Johnson, D. W.; Lindberg, S. E., eds. Atmospheric deposition and forest nutrient cycling. New York: Springer-Verlag: 178-195.

Welbourn, M. L.; Stone, E. L.; Lassoie, J. P. 1981. **Distributions of net litter inputs with respect to slope position and wind direction.** Forest Science. 27: 651-659.

**Appendix.**--Soil chemical and physical properties of treatment units by IMI category for each study area (standard errors in parentheses).

| | Frequent | | | Control | | | Infrequent | | |
|---|---|---|---|---|---|---|---|---|---|
| Item | Xeric | Intermediate | Mesic | Xeric | Intermediate | Mesic | Xeric | Intermediate. | Mesic |
| **ARCH ROCK** | | | | | | | | | |
| Sand (%) | 23.4 (1.3) | 24.8 (1.8) | 23.0 (1.2) | 30.6 (3.6) | 26.0 (4.0) | 23.9 (2.1) | 28.3 (2.6) | 27.7 (1.4) | 23.2 (2.1) |
| Silt (%) | 64.9 (1.6) | 63.5 (1.6) | 64.7 (1.5) | 55.0 (4.9) | 60.5 (4.5) | 64.6 (2.4) | 57.7 (4.1) | 58.3 (2.2) | 64.8 (2.5) |
| Clay (%) | 11.8 (0.5) | 11.8 (0.3) | 12.3 (0.3) | 14.3 (1.4) | 13.5 (0.5) | 11.5 (0.5) | 14.0 (1.5) | 14.0 (0.8) | 12.0 (0.8) |
| pH | 3.98 (0.22) | 3.70 (0.19) | 4.23 (0.15) | 3.61 (0.09) | 3.76 (0.14) | 3.89 (0.11) | 3.64 (0.10) | 4.06 (0.19) | 4.21 (0.26) |
| $NH_4$ (mg/kg soil) | 7.22 (1.27) | 11.79 (3.99) | 21.19 (3.54) | 7.83 (2.25) | 5.19 (2.47) | 12.43 (1.91) | 7.78 (2.66) | 13.55 (2.89) | 13.93 (4.51) |
| $NO_3$ (mg/kg soil) | 1.30 (1.07) | 0.23 (0.04) | 3.39 (0.77) | 0.17 (0.04) | 0.17 (0.06) | 1.94 (1.70) | 0.11 (0.05) | 1.08 (0.88) | 2.88 (1.59) |
| TIN (mg/kg soil) | 8.52 (1.92) | 12.02 (4.02) | 24.68 (3.69) | 8.01 (2.27) | 5.35 (2.41) | 14.37 (3.12) | 7.89 (2.68) | 14.63 (2.45) | 16.81 (5.84) |
| $PO_4$ (mg/kg soil) | 0.12 (0.03) | 0.14 (0.04) | 0.20 (0.03) | 0.14 (0.03) | 0.04 (0.01) | 0.11 (0.02) | 0.08 (0.01) | 0.15 (0.03) | 0.13 (0.03) |
| Ca (mg/kg soil) | 321.3 (143.0) | 110.8 (76.8) | 429.2 (64.5) | 174.8 (71.3) | 18.3 (9.9) | 155.4 (79.0) | 97.7 (38.6) | 414.8 (111.8) | 357.7 (164.8) |
| Mg (mg/kg soil) | 62.8 (22.0) | 36.3 (10.6) | 113.0 (22.1) | 38.2 (11.0) | 15.3 (4.0) | 31.4 (9.1) | 36.5 (6.6) | 118.5 (53.5) | 83.5 (29.2) |
| Al (mg/kg soil) | 180.5 (33.7) | 255.2 (50.2) | 93.9 (29.6) | 433.3 (62.4) | 262.9 (70.3) | 213.9 (34.6) | 371.1 (75.3) | 182.6 (68.1) | 150.7 (59.7) |
| Ca:Al ratio | 74.5 (73.5) | 0.5 (0.4) | 11.3 (7.7) | 0.3 (0.1) | 0. 1 (0.1) | 13.1 (12.6) | 0.2 (0.1) | 16.4 (13.3) | 69.9 (64.3) |
| Litter mass ($g/m^2$) | 392.4 (31.0) | 239.1 (70.2) | 316.6 (16.7) | 539.3 (105.6) | 494.8 | 488.1 (58.0) | 451.3 (52.5) | 409.7 (21.4) | 349.9 (18.3) |
| **BLUEGRASS RIDGE** | | | | | | | | | |
| Sand (%) | 18.0 (3.0) | 30.6 (1.4) | 32.5 (2.5) | 35.3 (1.2) | 38.0 (1.1) | 36.5 (1.5) | 34.0 (3.0) | 35.5 (2.6) | 34.3 (1.8) |
| Silt (%) | 70.5 (3.5) | 54.9 (2.1) | 52.5 (1.5) | 48.5 (2.4) | 42.9 (2.5) | 46.0 (2.0) | 48.7 (5.1) | 49.3 (3.3) | 50.8 (2.4) |
| Clay (%) | 11.5 (0.5) | 14.5 (0.8) | 15.0 (1.0) | 16.3 (1.1) | 19.1 (1.6) | 17.5 (0.5) | 17.3 (2.2) | 15.2 (0.8) | 14.8 (0.7) |
| pH | 3.80 (0.19) | 4.51 (0.16) | 4.66 (0.36) | 4.19 (0.29) | 4.50 (0.24) | 5.27 (0.08) | 3.71 (0.15) | 4.72 (0.26) | 4.72 (0.23) |
| $NH_4$ (mg/kg soil) | 6.80 (1.79) | 13.92 (1.24) | 15.81 (0.02) | 8.17 (1.77) | 11.8 (1.82)1 | 20.76 (4.21) | 6.80 (0.68) | 14.28 (2.47) | 12.01 (2.20) |
| $NO_3$ (mg/kg soil) | 0.28 (0.01) | 5.04 (3.20) | 7.30 (7.30) | 0.85 (0.47) | 1.04 (0.43) | 1.77 (1.27) | 0.27 (0.06) | 1.73 (0.80) | 3.75 (1.52) |
| TIN (mg/kg soil) | 7.08 (1.80) | 18.96 (3.29) | 23.10 (7.28) | 9.03 (2.15) | 12.85 (1.91) | 22.53 (5.48) | 7.06 (0.70) | 16.01 (2.49) | 15.76 (2.93) |
| $PO_4$ (mg/kg soil) | 0.14 (0.01) | 0.25 (0.01) | 0.24 (0.04) | 0.17 (0.03) | 0.24 (0.03) | 0.25 (0.04) | 0.18 (0.03) | 0.22 (0.04) | 0.24 (0.04) |
| Ca (mg/kg soil) | 858.2 (610.5) | 2198.9 (312.5) | 2278.6 (341.8) | 1805.8 (915.5) | 2781.0 (1011.1) | 5020.6 (495.7) | 1259.9 (446.0) | 3761.4 (955.3) | 2839.8 (466.5) |
| Mg (mg/kg soil) | 111.0 (52.5) | 293.4 (29.2) | 368.3 (63.6) | 228.6 (89.8) | 350.6 (79.0) | 439.4 (20.5) | 216.2 (48.7) | 487.5 (93.5) | 405.3 (57.7) |
| Al (mg/kg soil) | 182.5 (39.3) | 76.0 (21.8) | 26.8 (21.3) | 349.7 (99.0) | 196.5 (81.3) | 3.3 (1.4) | 518.0 (96.4) | 44.8 (21.6) | 30.6 (16.5) |
| Ca:Al ratio | 3.8 (3.1) | 170.7 (83.7) | 174.8 (147.7) | 533.2 (343.6) | 527.2 (407.1) | 1310.9 (664.2) | 6.1 (5.1) | 627.8 (330.6) | 288.2 (194.0) |
| Litter mass ($g/m^2$) | 386.4 (20.0) | 438.3 (11.7) | 524.4 | 299.3 | 472.8 (27.8) | 376.3 | 443.2 (35.3) | 322.2 (30.2) | 422.4 (60.3) |

**Appendix cont.**

| Item | Frequent | | | Control | | | Infrequent | | |
|---|---|---|---|---|---|---|---|---|---|
| | Xeric | Intermediate | Mesic | Xeric | Intermediate | Mesic | Xeric | Intermediate. | Mesic |
| WATCH ROCK | | | | | | | | | |
| Sand (%) | 26.5 (1.4) | 24.2 (1.4) | 25.0 (2.2) | 28.5 (3.2) | 24.5 (2.0) | 25.4 (1.3) | 27.3 (2.8) | 26.3 (0.3) | 23.9 (1.5) |
| Silt (%) | 62.0 (1.9) | 63.6 (2.0) | 62.3 (4.4) | 56.8 (4.9) | 63.0 (2.9) | 61.8 (2.3) | 59.3 (3.7) | 60.8 (0.5) | 65.1 (1.7) |
| Clay (%) | 11.5 (0.5) | 12.2 (0.8) | 12.8 (2.3) | 14.7 (1.8) | 12.5 (0.9) | 12.9 (1.1) | 13.3 (1.2) | 13.0 (0.4) | 11.0 (0.6) |
| pH | 4.21 (0.77) | 3.83 (0.11) | 3.53 (0.11) | 3.43 (0.08) | 3.93 (0.27) | 4.18 (0.20) | 3.53 (0.05) | 5.03 (0.46) | 5.31 (0.23) |
| $NH_4$ (mg/kg soil) | 8.53 (1.52) | 16.30 (3.29) | 13.32 (3.98) | 6.59 (0.80) | 15.00 (3.18) | 24.75 (7.17) | 10.64 (3.80) | 20.03 (3.39) | 15.40 (1.55) |
| $NO_3$ (mg/kg soil) | 0.17 (0.06) | 1.10 (0.81) | 0.17 (0.14) | 0.14 (0.03) | 3.05 (2.57) | 4.42 (1.84) | 0.43 (0.25) | 15.43 (8.71) | 37.99 (8.19) |
| TIN (mg/kg soil) | 8.70 (1.58) | 17.40 (3.77) | 13.49 (3.98) | 6.73 (0.80) | 18.06 (5.60) | 29.17 (8.28) | 11.07 (4.04) | 35.45 (7.35) | 53.38 (7.53) |
| $PO_4$ (mg/kg soil) | 0.07 (0.02) | 0.09 (0.02) | 0.06 (0.02) | 0.07 (0.01) | 0.08 (0.03) | 0.11 (0.02) | 0.08 (0.02) | 0.15 (0.02) | 0.18 (0.01) |
| Ca (mg/kg soil) | 93.2 (41.3) | 159.5 (54.9) | 86.2 (30.5) | 86.1 (51.2) | 287.5 (186.8) | 410.9 (173.5) | 54.5 (24.0) | 794.4 (367.0) | 1323.0 (213.0) |
| Mg (mg/kg soil) | 47.9 (15.1) | 49.2 (11.0) | 42.1 (14.5) | 28.5 (7.0) | 70.5 (25.8) | 107.0 (40.9) | 27.5 (4.3) | 184.4 (89.3) | 184.7 (34.3) |
| Al (mg/kg soil) | 460.3 (40.6) | 222.7 (50.2) | 253.4 (46.5) | 438.2 (57.7) | 208.0 (65.2) | 117.5 (27.6) | 275.6 (60.3) | 146.4 (83.7) | 26.0 (24.0) |
| Ca:Al ratio | 0.1 (0.0) | 2.7(1.8) | 0.3 (0.1) | 0.2 (0.1) | 10.4 (10.1) | 97.5 (92.5) | 1.9 (1.8) | 238.6 (145.9) | 649.7 (180.7) |
| Litter mass ($g/m^2$) | 357.8 (123.7) | 370.8 (48.2) | 299.1 (38.7) | 363.6 (28.6) | 403.4 (74.4) | 349.1 (27.1) | 504.5 (51.3) | 426.9 (23.2) | 375.0 (30.7) |
| YOUNG'S BRANCH | | | | | | | | | |
| Sand (%) | 25.8 (3.7) | 30.7 (1.1) | 23.8 (1.0) | 25.7 (3.3) | 27.7 (3.9) | 25.4 (1.6) | 26.0 (3.6) | 32.2 (3.0) | 25.8 (2.1) |
| Silt (%) | 61.8 (4.6) | 54.0 (1.5) | 64.0 (1.5) | 60.7 (4.7) | 60.0 (5.3) | 62.8 (2.5) | 61.0 (5.1) | 51.3 (5.6) | 62.0 (3.0) |
| Clay (%) | 12.3 (1.0) | 15.3 (0.6) | 12.2 (0.5) | 13.7 (1.5) | 12.3 (1.5) | 11.9 (1.0) | 13.0 (1.5) | 16.3 (2.9) | 12.3 (1.1) |
| pH | 3.52 (0.06) | 4.40 (0.31) | 4.53 (0.19) | 3.63 (0.52) | 4.79 (0.45) | 4.95 (0.21) | 3.69 (0.03) | 4.30 (0.20) | 4.90 (0.32) |
| $NH_4$ (mg/kg soil) | 3.62 (0.09) | 8.95 (1.77) | 9.96 (2.58) | 3.66 (0.52) | 7.80 (1.55) | 10.66 (1.06) | 5.39 (1.04) | 10.08 (3.60) | 10.89 (1.92) |
| $NO_3$ (mg/kg soil) | 0.47 (0.11) | 1.70 (2.17) | 12.72 (6.00) | 0.56 (0.14) | 3.98 (2.03) | 10.04 (3.06) | 0.68 (0.03) | 2.59 (1.72) | 10.79 (6.40) |
| TIN (mg/kg soil) | 4.09 (0.16) | 10.64 (2.17) | 22.67 (8.11) | 4.22 (0.41) | 11.79 (2.71) | 20.70 (3.21) | 6.07 (1.05) | 12.67 (5.29) | 21.68 (7.96) |
| $PO_4$ (mg/kg soil) | 0.14 (0.03) | 0.43 (0.09) | 0.29 (0.05) | 0.12 (0.03) | 0.24 (0.09) | 0.27 (0.04) | 0.15 (0.07) | 0.29 (0.08) | 0.25 (0.03) |
| Ca (mg/kg soil) | 69.7 (20.5) | 808.3 (313.0) | 628.8 (151.0) | 100.6 (40.6) | 919.3 (396.6) | 884. 0 (158.1) | 108.5 (62.5) | 807.0 (273.7) | 899.1 (391.4) |
| Mg (mg/kg soil) | 20.6 (6.2) | 92.0 (17.9) | 61.9 (9.6) | 23.5 (6.1) | 82.5 (16.2) | 92.6 (16.3) | 33.6 (14.3) | 125.2 (41.7) | 97.6 (19.2) |
| Al (mg/kg soil) | 325.9 (47.5) | 166.6 (75.1) | 57.9 (31.4) | 405.9 (51.3) | 72.1 (64.2) | 28.4 (23.2) | 332.6 (57.4) | 152.5 (57.0) | 79.4 (39.7) |
| Ca:Al ratio | 0.18 (0.07) | 163.1 (141.3) | 168.5 (85.1) | 0.17 (0.05) | 142.9 (123.9) | 800.7 (547.2) | 0.2 (0.1) | 43.7 (26.8) | 391.4 (148.1) |
| Litter mass ($g/m^2$) | 546.4 (60.5) | 600.4 (48.0) | 548.8 (33.9) | 374.4 (3.0) | 368.4 (12.8) | 409.6 (73.0) | 536.1 (98.8) | 642.7 (34.9) | 677.3 (121.8) |