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Condition of Soils in Eastern Rivers and Mountains Network Parks

Natural Resource Technical Report NPS/ERMN/NRTR—2014/891

ON THE COVER
Collecting soil data in a long-term monitoring plot in Delaware Water Gap National Recreation Area.
Photograph by: Stephanie Perles.

Condition of Soils in Eastern Rivers and Mountains Network Parks

Natural Resource Technical Report NPS/ERMN/NRTR—2014/891

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List of Acronyms

ALPO: Allegheny Portage Railroad National Historical Park

BLUE: Bluestone National Scenic River

DEWA: Delaware Water Gap National Recreation Area

ERMN: Eastern Rivers and Mountains Network

FONE: Fort Necessity National Battlefield

FRHI: Friendship Hill National Historic Site

GARI: Gauley River National Recreation Area

JOFL: Johnstown Flood National Memorial

NERI: New River Gorge National River

NPS: National Park Service

Executive Summary

As part of the nationwide National Park Service Inventory and Monitoring Program, the Eastern Rivers and Mountains Network (ERMN) is monitoring forest soil resources in eight parks located in West Virginia, Pennsylvania, and New Jersey. Soils are natural resources critical to the parks, an important component of terrestrial ecosystem health, and a resource that is highly sensitive to anthropogenic stressors. Soil resources are influenced by numerous factors including underlying bedrock, topography, biota, atmospheric inputs, historical land-use, and the interactions of these factors.

An important threat to soil resources on National Park Service lands is air pollution. Two of the most important pollutants are sulfur (S) and nitrogen (N), both of which can contribute to acidification of soil and surface water resources. Acidic precipitation can cause both short- and long-term changes in soil nutrients, thereby changing the availability of these necessary nutrients to plants. Three important impacts to terrestrial ecosystems that can result from atmospheric S and N deposition are a) toxicity of aluminum (Al) to plant roots and foliage, b) depletion of calcium (Ca) and other key soil nutrients, and c) nitrogen saturation in soil that leads to nitrate leaching into surface waters.

Soils in ERMN parks are monitored at permanent long-term vegetation monitoring plots. Data summaries presented in this report are based on laboratory analyses of soil samples collected between 2007 and 2010, with a total of 245 O horizon samples and 334 A horizon samples collected from 348 monitoring plots. Specifically, we:

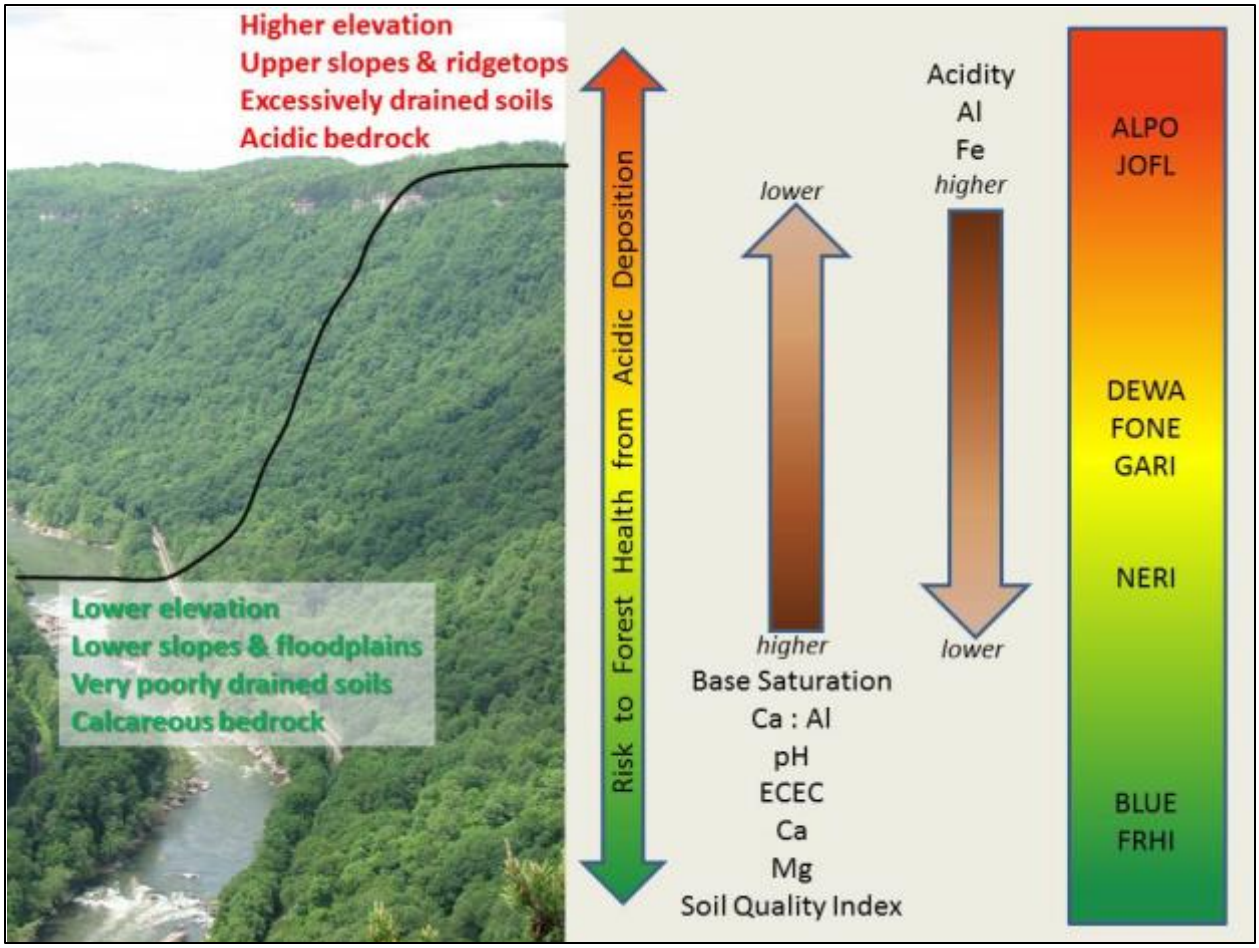
1. summarize the baseline monitoring data collected on ERMN soils that will be used as the basis for long-term monitoring; and

2. examine relationships among site characteristics, stressors, and soil properties, and what these relationships suggest about forest ecosystem health.

We adopted an exploratory data analysis approach to examine and visualize the main characteristics of the ERMN soil data, focusing on 20 soil chemical variables. We summarized soil variables by park and examined potential patterns among 14 site characteristics and soil variables. Data summaries are provided in Appendixes B, C, D, E, and F. These data provide an important baseline with which to analyze trends in soil condition as additional soil samples are collected in the future for comparison.

Differences in soil variables among and within parks can be explained by several interacting factors that affect the soil chemical properties, including elevation, landscape position, bedrock geology, and soil drainage. These patterns are described in the diagram on the next page.

In general, lower elevations, lower landscape positions, more calcareous bedrock geology, and poor soil drainage are associated with higher values of the following soil variables: base saturation, molar ratio of exchangeable calcium to aluminum, pH, effective cation exchange capacity, exchangeable calcium, exchangeable magnesium, and soil quality index. Whereas, higher elevations, higher



Executive Summary Figure. Conceptual Diagram of the patterns observed between soil chemical properties and environmental factors (elevation, landscape position, bedrock geology, and soil drainage). Park acronyms are defined on page xii.

landscape positions, more acidic bedrock geology and well-drained soils are associated with lower values of the aforementioned soil variables. Acidity, aluminum, iron, carbon, and nitrogen, however, are higher at higher elevations, higher landscape positions, more acidic bedrock geology, and well-drained soils.

These patterns strongly influence the forests' vulnerability to acidification. Well-drained soils over acidic bedrock on upper slopes and ridgetops support forests that are more at risk of deleterious effects of acidic deposition because the soils have depleted cation nutrients, less buffering capacity, and higher concentrations of aluminum that can be toxic to plants. Forests on lower slopes, more calcareous bedrock, and poor soil drainage are less at risk since these forests tend to have richer soils with more available cation nutrients, more buffering capacity, and lower non-toxic concentrations of aluminum.

These differences are illustrated clearly within DEWA where acidic soils on ridgetops and upper slopes are very susceptible to acidic deposition effects when compared with richer soils that occur in the river valley over limestone bedrock. Similar patterns are observed in NERI and GARI when ridgetop soils are compared with valley soils. Of the ERMN parks, BLUE and FRHI are least vulnerable to acidic deposition because of the calcareous-influenced bedrock that forms richer soils with more buffering capacity. On the opposite end of the risk spectrum, ALPO and JOFL occur at higher elevations and in areas of high deposition of sulfur and nitrogen, which causes the soil in those parks to be more sensitive to negative effects of acidic deposition.

Forests have a fixed capacity to store nitrogen, and when nitrogen inputs exceed this storage capacity, the forest becomes nitrogen saturated. One way to measure the amount of nitrification occurring in soil is by the ratio of carbon to nitrogen (C:N). The C:N ratio in ERMN park soils is influenced by geology, landscape position, and soil drainage class. In general, soils on upper slopes and ridgetops, over acidic rock and well-drained soils had higher C:N ratio than soils on low slopes and floodplains, poorly-drained soils, and soils over calcareous bedrock (which tend to occur at lower elevations). Typically, as C:N ratio decreases, the amount of nitrate that is exported from the soil increases. However, nitrification increases sharply when C:N ratio decreases below 20–25 when the forested system is considered to be nitrogen saturated. In ERMN parks, forests that are more at risk for nitrogen saturation and the subsequent negative consequences are at lower slopes, over more calcareous rock, and on more poorly-drained soils. This is opposite from forests that are at high risk from acidification (soils on the higher slopes, acidic rock, and well-drained soils). However, the C:N ratios may be more influenced by tree species composition, land use history, and previous disturbance regimes than by the environmental factors explored here.

The exploratory data analyses presented here provide context with which to view ERMN soil monitoring data. These data provide an important baseline with which to analyze trends in soil condition as additional soil samples are collected in the future.

Introduction

As part of the nationwide National Park Service (NPS) Inventory and Monitoring (I&M) Program (Fancy et al. 2009), the Eastern Rivers and Mountains Network (ERMN) is monitoring forest soil resources in eight parks located in West Virginia, Pennsylvania and New Jersey (Figure 1). Long-term monitoring of forest soils was identified as a high priority for ERMN due to the importance of soils as a natural resource critical to the parks, an important component of terrestrial ecosystem health, and a resource that is highly sensitive to anthropogenic stressors.

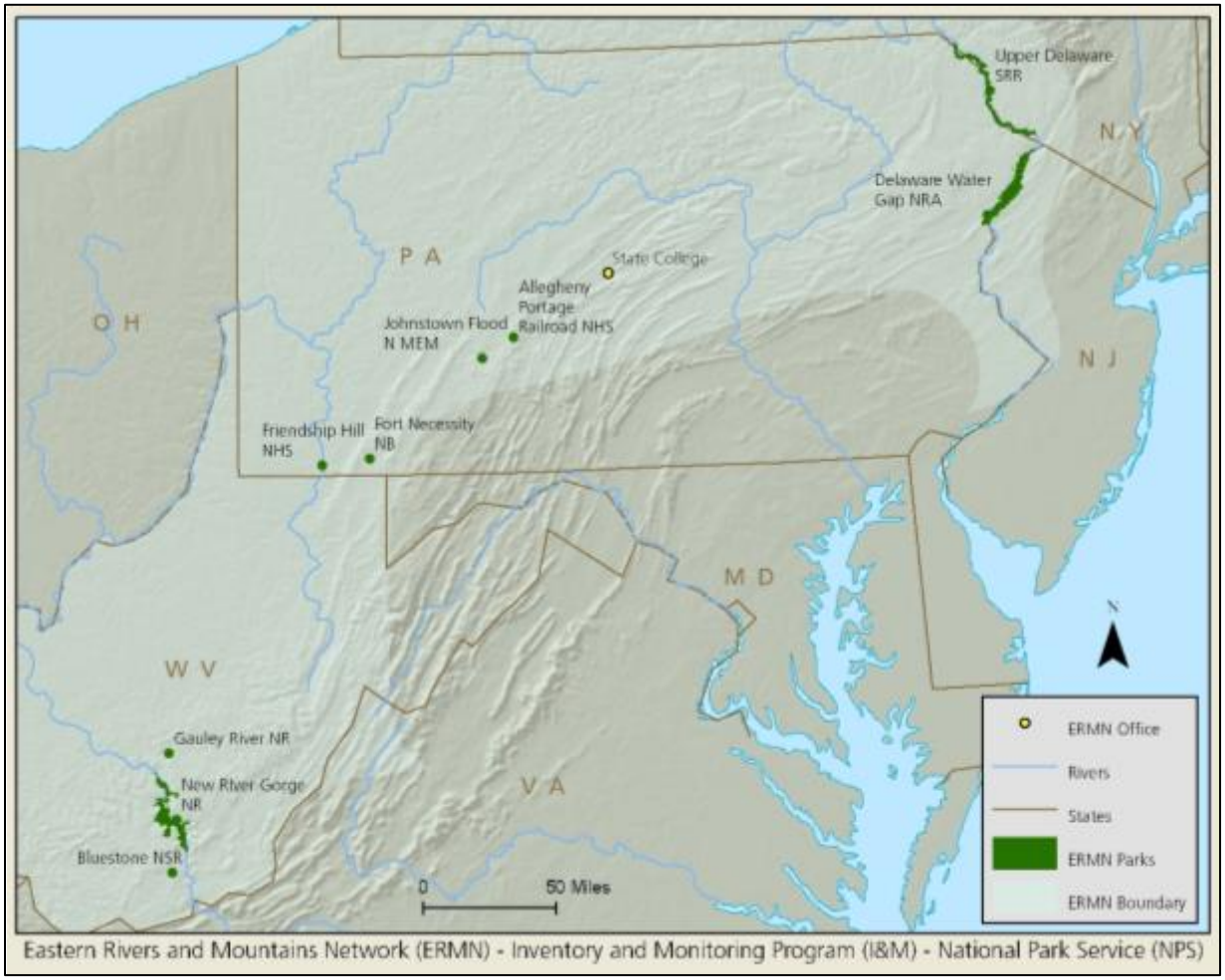


Figure 1. Location of parks in the Eastern Rivers and Mountains Inventory and Monitoring Network.

Processes Affecting Forest Soil Resources (adapted from Rentch 2006)

Forest plants require five primary resources: light, carbon dioxide (CO_2), water, mineral nutrients, and a porous media for physical rooting and support (Barnes et al. 1998). Plants obtain light from solar radiation and CO_2 from the atmosphere; the remaining resources are provided by soil. Soil resources determine the maximum potential productivity and structural diversity of vegetation (Chapin et al. 1996). Soil resources are influenced by numerous factors, including underlying bedrock, topography, biota, historical land-use, and atmospheric inputs, as well as the interactions of these factors.

Soil properties and nutrient levels are strongly affected by the underlying bedrock geology and the rate at which the parent material weathers. Soil resources in the northeastern U.S. are also strongly influenced by glacial geology, which resulted in a mosaic of erosional and depositional features throughout the region. Temperature and precipitation patterns, as they interact with parent materials and topography, are important in determining soil processes and soil development (Barnes et al. 1998). In turn, the rate of weathering of parent material and soil development is strongly modified by soil biota; particularly through carbonic acid weathering and the production of organic acids in the upper soil profile (Schlesinger 1997).

Topography is another important factor that affects soil resources. Where parent materials are similar between sites, north- and east-facing slopes have higher organic matter content, pH, base saturation, and more extractable nitrogen than south- and west-facing slopes that are generally warmer, especially in winter (Tajchman 1983). South- and west-facing slopes also have deeper, more heavily weathered and leached soils. Trees on nutrient-poor, southwest-facing sites are more conservative of nutrients and produce nutrient-poor litter compared to trees of the same species on richer mesophytic sites (Boerner 1984). In north-central West Virginia, Hicks and Frank (1984) found significant positive correlations between transformed aspect and soil cation exchange capacity (CEC), organic matter, phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and total base saturation for soil A horizons, and, to a lesser extent, B horizons. They attributed this difference, in part, to a more rapid decomposition and recycling rate of litter on north- and east-facing sites.

The ecosystem's plants are also important influences on soil resources. Chemical composition and decomposition rates of leaf litter produced by plants greatly affect soil (Hobbie 1992). For example, Johnson et al. (1985) found that yellow-poplar (*Liriodendron tulipifera*) stands had greater total nitrogen (N), total P, and exchangeable Ca and Mg than oak-hickory (*Quercus* spp. and *Carya* spp.) and chestnut oak (*Quercus prinus*) stands. Invasive exotic plants, in particular, can have profound impacts on soil biota, with subsequent impacts on biogeochemical cycling, plant growth, and disturbance regimes (Wolfe and Klironomos 2005).

Soil biota are poorly understood but critical for many ecosystem processes (decomposition, mineralization, nutrient cycling, and forest development). Soil biota include microfloral components (bacteria, fungi, and algae), microfaunal components (nematodes, microarthropods, and protozoans), and macrofaunal components (earthworms, ants, and termites). Soil biota also include mycorrhizal fungi, organisms that form symbiotic relationships with roots of many plants. This symbiotic partnership provides water and nutritional benefits to the host plant in exchange for carbohydrates to

the fungi (Read 1997; Fitter et al. 1999). Acid deposition (see discussion below) may change the mycorrhizal community composition, which in turn may affect vegetative germination and growth rates, species richness, and rates of natural forest development (Blaney and Miller 1995). Ectomycorrhizal fungal communities have been shown to be sensitive to nitrogen deposition (Arnolds 1991, Lilleskov and Bruns 2001).

Where they occur, earthworms are “keystone” soil fauna which control many aspects of soil structure and nutrient cycling (Hendrix 1995). Earthworms are native to North America south of the extent of the Wisconsinan glaciation (Hendrix and Bohlen 2002). However, introduction of exotic earthworms can have profound effects on soil and vegetation, including alteration of soil mineral horizons, elimination of the soil organic horizon, changes to the rate at which leaf litter is cycled, alteration of the soil microbial and fungal communities, significant reductions in herbaceous plant diversity and cover, shifts in herbaceous species composition, reduction in tree seedling density, and introduction of pathogens (Alban and Berry 1994; Proulx 2003; Bohlen et al. 2004a,b, Hale et al. 2006). The most dramatic effects of exotic earthworms have been recorded in glaciated ecosystems previously devoid of earthworms (such as in New England and the Upper Midwest). In areas inhabited by native earthworms, successful invasions by exotic earthworms have been documented after soil or vegetation disturbance (Hendrix and Bohlen 2002).

Historical land use can influence soil properties for decades and even centuries. Nearly a century after the cessation of agriculture, formerly cultivated forested sites in New England had lower soil carbon-to-nitrogen ratio and higher rates of nitrification compared with soils from sites that had continually been forested (Compton and Boone 2000). The duration of pasturing over the last century in a forest in western Belgium was found to be negatively correlated with the carbon-to-nitrogen ratio and positively correlated with pH in present day soils (Verheyen et al 1999). In southern Appalachian forests, Fraterrigo et al. (2005) found that in former pastures, the spatial distribution of soil nutrients tended to be homogenized, while forest stands that had been logged tended to have highly variable spatial distribution of soil nutrients. In northern hardwood forests in New Hampshire, forest stands that have experienced disturbances, such as logging, fire, wind, and agriculture, have higher carbon-to-nitrogen and lower nitrification rates than old growth forest stands (Goodale and Aber 2001).

Air Pollution (adapted from Sullivan et al. 2011a,b)

Air pollution is an important threat to soil resources on NPS lands. Air pollution includes atmospheric pollutants, such as aerosols, particulates, ozone, and cumulative deposition of hydrogen ions (H^+), nitrogen (NO_x, NH_3) and sulfur (SO_4) via wet and dry processes. Two of the most important pollutants in the ERMN are sulfur (S) and nitrogen (N), both of which can contribute to acidification of sensitive soil and surface water resources. The addition of S and N from air pollution sources to national park ecosystems can alter plant, animal, and soil communities and influence the mix of species that thrive in those ecosystems.

The amounts of S and N emitted into the atmosphere vary across the United States; generally, with highest emissions near coal-fired power plants, major population centers, and centers of energy, agricultural, and industrial development. Sulfur emissions in the United States derive primarily from electricity-generating power plants using high-sulfur coal, and secondarily from industrial and

mobile sources. Sulfur is commonly emitted into the atmosphere as sulfur dioxide (SO_2), released when S-containing coal or other fuel is burned. There are two major kinds of human-caused emissions of N into the atmosphere in the United States: NO_x and NH_3. The oxidized forms (primarily NO_x) derive mainly from motor vehicles, power plants, and industrial facilities. The reduced forms (primarily NH_3) derive mainly from agriculture, via volatilization of N contained in animal manures and fertilizers.

Acid deposition is the byproduct of the sulfuric and nitrogen oxides that are released into the atmosphere from the burning of fossil fuels, automobile exhaust, and industrial processes. When these pollutants mix with water vapor, sulfur and nitric acids are formed. Acid deposition can occur as either wet (rain or snow) or dry deposition, as particles of vapor, cloud, or fog deposition (Driscoll et al. 2001). Chronic acidification generally refers to streams, lakes, and soil ecosystems that have lost their ability to neutralize acidifying events. Episodic acidification typically occurs during periods of high stream flow associated with rainstorms or snowmelt and is, by definition, a short-term decrease in acid neutralizing capacity. Base nutrients, such as Ca, K, and Mg, and other types of neutralizing chemicals, normally buffer changes in ecosystem acidity; however, when ecosystems are exposed to excessive, long-term acid deposition, these elements can become depleted. This can make the system more vulnerable to episodic acidification events and may lead to chronic surface water acidity, as well as nitrogen saturation of forest soils (Aber et al. 1998). Areas in the Northeastern U.S. composed of thin acidic soils with low buffering capacity are especially sensitive to acid deposition (Driscoll et al. 2001).

Air Pollution in the Eastern Rivers and Mountains Network (adapted from Sullivan et al. 2011a, b)

Precipitation in the central Appalachian Region is among the most acidic in the United States and pH readings below 4.0 are common in summer months (Rentch and Hicks 2000). The total S deposition in the Eastern Rivers and Mountains Networks (ERMN) is quite high in comparison to other NPS Inventory and Monitoring networks. Most parks in the network receive 10 to 20 kg S/ha/yr; however Allegheny Portage Railroad National Historic Site (ALPO), Johnstown Flood National Memorial (JOFL), Forest Necessity National Battlefield (FONE), and Friendship Hill National Historic Site (FRHI) receive more than 30 kg S/ha/yr—some of the highest rates of S deposition in the United States (Figure 2).

Given these deposition rates, recent reports (e.g., Sullivan et al. 2011a) ranked ERMN parks as very high risk for acidic deposition exposure. The sensitivity of park ecosystems was also ranked very high, since the geology and water within network parks are known to be acid-sensitive; there are acid-sensitive tree species present, and slopes are steep, which give rise to low-order, relatively high-gradient streams. The overall level of concern for acidification effects on ERMN parks is considered high by Sullivan et al (2011a).

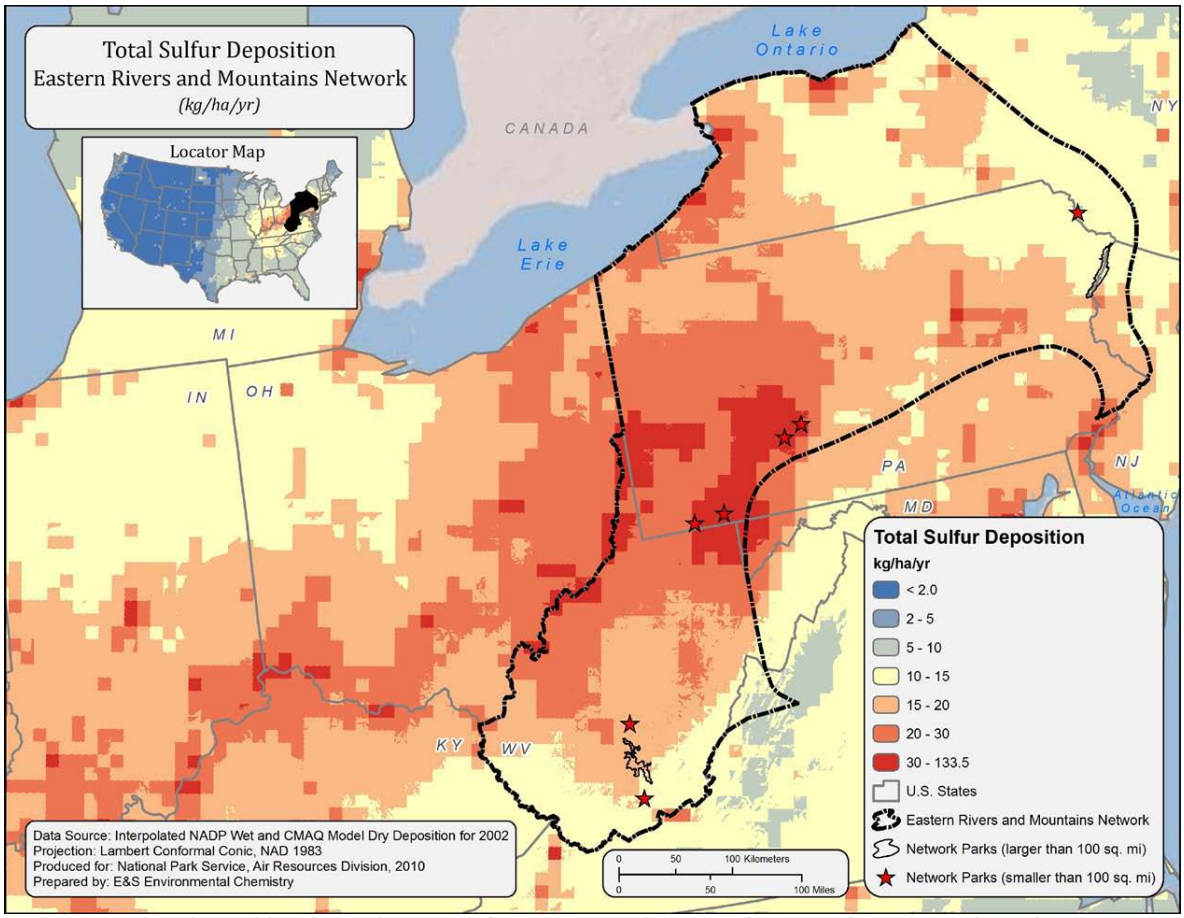


Figure 2. Total S deposition in and around the Eastern Rivers and Mountains Network. Values are expressed as kilograms of S deposited per hectare per year (see Sulivan et al. 2011a for details).

Total N deposition in the ERMN varies between 5–15 kg N/ha/yr (Figure 3); however, N deposition of about 10 kg N/ha/yr or higher can be associated with appreciable amounts of nitrate (NO_3^-) leaching into surface waters in the eastern United States (U.S. EPA 2008). ALPO and JOFL receive a slightly higher level of N deposition, 15–20 kg N/ha/yr, than the other network parks. Compared to other NPS I&M Networks, the ERMN experiences one of the highest levels of N pollutant exposure, since N emissions and N deposition within the network are both very high. However, there are few ecosystems in the ERMN that are highly sensitive to nutrient enrichment. Therefore, the overall level of concern for nutrient N enrichment effects on ERMN parks is considered very low (Sullivan et al. 2011a and 2011b).

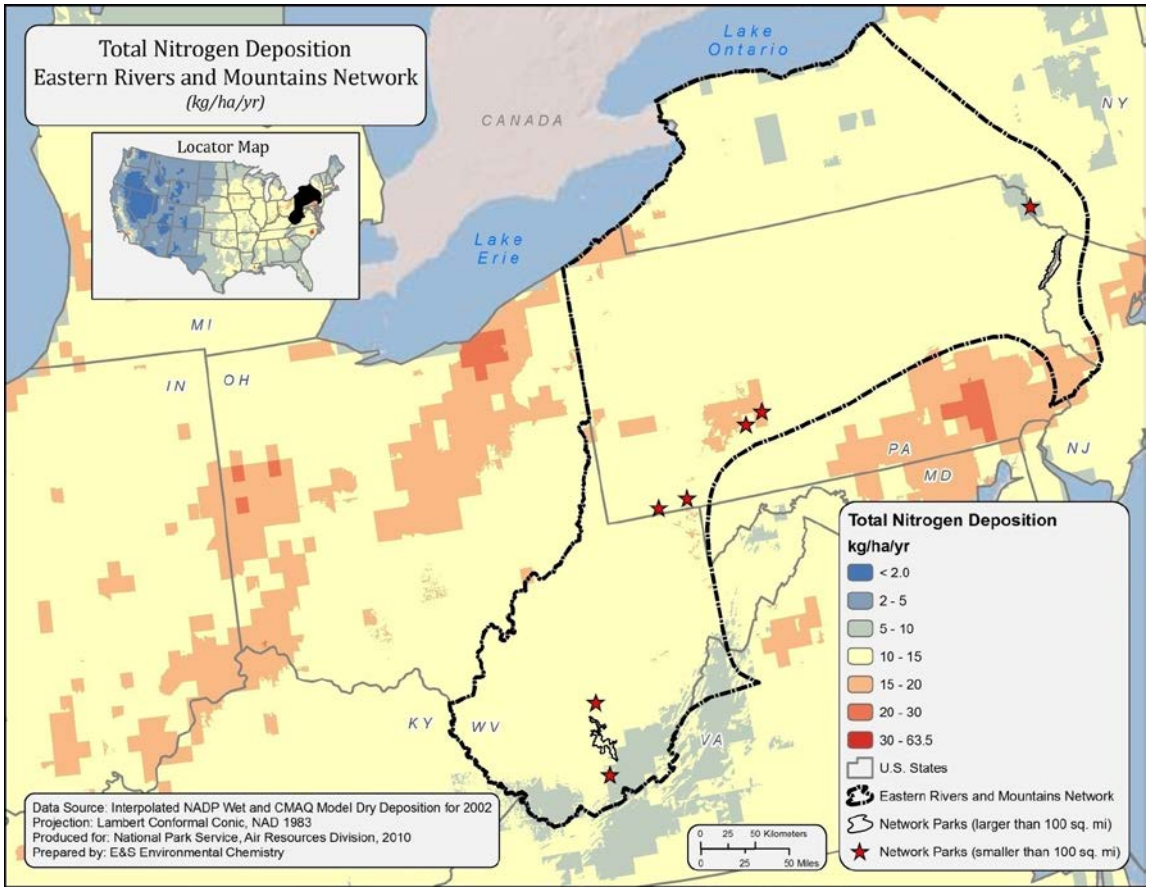


Figure 3. Total N deposition in and around the Eastern Rivers and Mountains Network. Included in the total are wet plus dry forms of both oxidized (nitrogen oxides, NOx) and reduced (ammonia, NH3) N. Values are expressed as kilograms of N deposited per hectare per year (see Sullivan et al. 2011a and 2011b for details).

Effects of Sulfur and Nitrogen Deposition on Park Ecosystems

Acidic precipitation can cause both short-term and long-term changes in soil nutrients, thereby changing the availability of these necessary nutrients to trees. There are three major potentially important impacts to terrestrial ecosystems from atmospheric S and N deposition:

Toxicity of Aluminum (Al) to Plant Roots and/or Foliage

At high concentration in soil water, Al is toxic to plant roots. Reduced root growth and damage to root tips limits the ability of plants to take up water and nutrients, especially $Ca^{2+}$and Mg^{2+} (Shortle and Smith 1988, Parker et al. 1989, McLaughlin et al. 1991, Cronan and Grigal 1995, Shortle et al. 1997, DeHayes et al. 1999, Schneck et al. 1999).

Depletion of $Ca^{2+}$and Other Key Soil Nutrients (Base Cations)

Nutrient base cations, including Ca, Mg, and K, are taken up through plant roots from soil water to satisfy plant nutritional needs. Inputs of S and N in acidic deposition accelerate leaching of these key nutrients from the soil, which can cause damage to acid-sensitive plants (Cronan et al. 1978). At the ecosystem level, acid precipitation has been linked to Ca^{2+} depletion in northeastern (Lawrence et al.

1995), central Appalachian (Adams 1999), and southeastern forests (cited in Lawrence and Huntington 1999). In soils having low base saturation, exchangeable Ca^{2+}, Mg^{2+}, or K^{+} can be depleted to a level that nutrient deficiencies develop in vegetation. The soil's ability to maintain its pH is also affected. Several studies in Pennsylvania have shown sugar maple decline linked to relatively high levels of acidic deposition on soils with low base cation supply and Ca^{2+} depletion. Trees that grow on soils having low base cation supply are stressed and, consequently, often become more susceptible to damage from defoliating insects, drought, and extreme weather (Long et al. 1997, Horsley et al. 1999, Demchik and Sharp 2004). Dieback and mortality of susceptible trees occurs predominately on ridgetops and on upper slopes, where soil base cation availability is much lower than at middle and lower slopes (Bailey et al. 1999). Acid precipitation has also been linked to increased susceptibility of trees to pests or pathogens. Predisposition to disease may result from altered resource allocation or carbon metabolism; if additional demands are placed on carbon resources for defense compounds, there may be insufficient photosynthate available for other tree processes (Taylor et al. 1994).

Nitrogen Saturation

Forests have a fixed capacity to store N in the soil and trees that varies depending on the plant species present and the land-use history. When N inputs exceed this storage capacity, the forest becomes N saturated. In the early stages of N saturation, the trees may actually grow faster because they are being fertilized by N, which is the most important growth-limiting nutrient in many forests. However, as the soil approaches N saturation, more of the incoming N leaches as nitrate (NO_3^-) to soil water and eventually to streams and lakes. This leaching of NO_3^- can contribute to soil acidification and base cation depletion, which, in turn, causes deteriorating tree health and increased mortality in sensitive tree species during the latter stages of N saturation (U.S. EPA 2008).

Land use history plays a significant role in preconditioning forest response to nitrogen deposition (Aber et al. 1998, Goodale and Aber 2001). The greater the previous extraction of nitrogen (by fires or forest harvesting) was, the greater the nitrogen limitation, and the larger the amount of nitrogen deposition necessary to move a site toward saturation. Time periods involved may be as large as 100–200 years. Overall, Aber et al. (1998) found that previous land use history was as important as either total or current nitrogen deposition in determining current leaching losses in the northeastern U.S.

Objectives

This report presents soil data collected in ERMN parks between 2007 and 2010. Specifically, we:

1. summarize baseline monitoring data collected on ERMN soils that will be used as the basis for long-term monitoring; and
2. examine relationships among site characteristics, stressors, and soil properties, and what these relationships suggest about forest ecosystem health.

These data provide an important baseline with which to analyze trends in soil condition as additional soil samples are collected in the future. Of the samples collected between 2007 and 2010, the soil remaining after laboratory analysis have been archived so that the archived samples can be re-analyzed using contemporary methods when the same soils are sampled and analyzed in the future. As soils are resampled, ERMN will focus on the following indicators to report on trends in soil condition:

1. Percent base saturation as an indicator of soil fertility;
2. Ca:Al molar ratio and Al content as indicators of potential toxicity;
3. pH as an indicator of acidity;
4. Cation exchange capacity as an indicator of acid neutralization potential; and
5. C:N ratio as an indicator of N-saturation.

Methods

Sampling Procedures

Soils in ERMN parks are monitored at permanent long-term vegetation monitoring plots which were established in order to report on the status and trends of forest resources within the parks (Perles et al. 2014). A brief overview of the soil monitoring methods is provided here; a detailed rationale of the sampling design and methods and Standard Operating Procedures, are provided in Perles et al. (2014).

Locations of the permanent monitoring plots in each park were determined using generalized random tessellation stratified sampling (GRTS; McDonald 2004, Stevens and Olsen 2004). This design employs random plot selection, allowing for statistical inference while also providing balanced spatial coverage and flexibility for post-stratification of plots based on ecological system or other criteria as needed over the long term. All plots are revisited at four-year intervals; thus, 25% of the plots are sampled annually in each ERMN park.

The vegetation monitoring plots are circles with a 15-m radius. At each plot, three soil samples are collected from sampling frames located adjacent to the plot's northern edge. One sample is collected from each of three 2-m radius circle sampling frames. A 10×10-cm quadrat is used to identify the sampling area within the 2-m radius sampling frame. Depth of leaf litter is measured on two sides of the quadrat. Leaf litter inside the quadrat is then collected to be weighed once it has dried. Then the soil within the quadrat is removed and collected by genetic horizons (e.g., O, A, and/or B), storing soil from each horizon separately. Soil is typically collected to a depth of <15 cm. The thickness and color of each horizon is recorded. The presence or absence of earthworms is noted.

Soil sampling began in 2007 in the ERMN. Analyses were based on samples collected between 2007 and 2010, with a total of 245 O horizon samples and 334 A horizon samples collected from 348 monitoring plots (Table 1). At some plots, the O and/or A horizons were absent or too thin to collect accurately; in these cases, these soil horizons were not sampled.

Table 1. Number of soil samples and monitoring plots in each park.

Park	Code	State	Number of Plots	Number of O Samples	Number of A Samples
Allegheny Portage Railroad NHS	ALPO	PA	18	16	18
Bluestone NSR	BLUE	WV	40	15	39
Delaware Water Gap NRA	DEWA	PA/NJ	102	80	94
Fort Necessity NB	FONE	PA	20	15	20
Friendship Hill NHS	FRHI	PA	20	6	20
Gauley River NRA	GARI	WV	40	30	39
Johnstown Flood NMem	JOFL	PA	8	7	8
New River Gorge NR	NERI	WV	100	76	96
Total			348	245	334

NRA is a National Recreation Area; NB is a National Battlefield; NHS is a National Historic Site; NSR is a National Scenic River; NMem is a National Memorial.

Laboratory Analysis

Soil samples were air dried and then chemically analyzed at the Analytical Lab at the University of Maine. Soil pH was measured in distilled water. Organic matter was measured by loss on ignition (LOI) at 550ºC. Total nitrogen and carbon were measured by combustion analysis at 1,350ºC. Exchangeable acidity was extracted in potassium chloride and measured by titration. Exchangeable cations and phosphorous were extracted in ammonium chloride and measured by inductively coupled plasma with optical emission spectrometry (ICP-OES). All values for cations reported here are extractable concentrations, not total soil concentrations. From the chemical analysis, several additional variables were calculated, including effective cation exchange capacity (ECEC), percent base saturation, molar Ca:Al ratio, C:N ratio, and N:P ratio (Table 2). The soil quality index was also calculated for each sample following Amacher et al. (2007).

Table 2. Soil chemistry variables used in exploratory data analysis.

Soil Chemistry Variable	Abbreviation	Formula
pH	soil pH	Direct measure
Exchangeable acidity (meq/100g)	acidity	Direct measure
Calcium (mg/kg)	Ca	Direct measure
Aluminum (mg/kg)	Al	Direct measure
Magnesium (mg/kg)	Mg	Direct measure
Potassium (mg/kg)	K	Direct measure
Sodium (mg/kg)	Na	Direct measure
% Total Carbon	TC	Direct measure
% Total Nitrogen	TN	Direct measure
% Loss of Ignition	LOI	Direct measure of soil organic matter
Phosphorus (mg/kg)	P	Direct measure
Iron (mg/kg)	Fe	Direct measure
Manganese (mg/kg)	Mn	Direct measure
Zinc (mg/kg)	Zn	Direct measure
Soil Quality Index	SQI	See Amacher et al. (2007)
Effective cation exchange capacity[1]	ECEC	(Ca + K + Mg + Na + acidity)
% Base Saturation[1]	BaseSat	((Ca + K + Mg + Na) / ECEC) *100
Calcium : Aluminum ratio	Ca:Al	(Ca / 40.078) / (Al / 26.981)
Carbon : Nitrogen ratio	C:N	TC / TN
Nitrogen : Phosphorus ratio	N:P	TN / P

[1] For these variables, cations were first converted to meq / 100g using this formula:
Cation (mg/kg) / ((Cation atomic weight / valence)*10).

Data Analysis

Due to the many soil variables and the complexity of interpreting soil data, we adopted an exploratory data analysis (EDA) approach to examine and visualize the main characteristics of ERMN soil data. The objectives were to summarize soil variables by park and to examine potential patterns among site characteristics (Table 3), stressors, and soil variables. We used box plots, histograms, scatter plots, and standard descriptive statistics (mean, standard error) to summarize and explore the data.

Table 3. Environmental variables used in exploratory data analysis.

Environmental Variable	Data Type	Units or Categories	Source
Geology	Categorical	A = more acidic, B = intermediate, C = more calcareous	See Appendix A
Landscape Position	Categorical	Upper, Middle, Lower	ERMN Forest Health Data
Elevation	Quantitative	Meters above sea level	ERMN Forest Health Data
Aspect	Categorical	N, NE, E, SE, S, SW, W, NW	ERMN Forest Health Data
Aspect (Beers Transformed)	Quantitative	Unit-less value between 0–1	Beers et al. 1966
Slope	Quantitative	Degrees	ERMN Forest Health Data
Vegetation type	Categorical	Xeric, Mesic, Floodplain, Successional	ERMN Forest Health Data
Soil Parent Material	Categorical	Alluvium, Colluvium, Residuum, Glaciofluvial, Till, Fill	NRCS Soil Surveys[1]
Depth to Restrictive Layer	Quantitative	Inches	NRCS Soil Surveys[1]
Type of Restrictive Layer	Categorical	Fragipan, Lithic, Paralithic, None	NRCS Soil Surveys[1]
Soil Taxonomy	Categorical	Analyzed Order, Suborder, and Great Group separately	NRCS Soil Surveys[1]
Soil Drainage Class	Categorical	Very poorly drained to excessively drained	NRCS Soil Surveys[1]
Sulfur deposition	Quantitative	kilograms / hectare / year	Sullivan et al. 2011a
Nitrogen deposition	Quantitative	kilograms / hectare / year	Sullivan et al. 2011b

[1] USDA 2013 a, b, c, d, e, f, g, and h. The scale for the soil surveys range from 1:1200–1:2400 and were intended for interpretation at those scales. ERMN monitoring plots are much smaller than the soil surveys minimum mapping unit. Plots may fall in inclusions within the map units; thus, soil samples from ERMN plots may differ from the mapped soils.

Results

Environmental Variables

Of the environmental variables examined, bedrock geology, landscape position, elevation, and soil drainage class seem to be the most influential characteristics on soil chemical properties. No patterns were observed between soil variables and aspect, vegetation group, slope, depth to restrictive layer, type of restrictive layer, sulfur deposition, or nitrogen deposition. Graphs showing the soil variables plotted against geology group, landscape position group, elevation, and soil drainage class are shown in Appendix B, C, D, and E, respectively. Data from O horizon and A horizon samples are graphed separately.

A conceptual diagram of the relationships between the soil variables and bedrock geology, landscape position, elevation, and soil drainage class is shown in Figure 4. In general, in ERMN parks, lower elevations, lower landscape positions, more calcareous bedrock geology, and poor soil drainage are associated with higher values of the following soil variables: base saturation, Ca:Al ratio, pH, ECEC, Ca, Mg, and soil quality index. Whereas, higher elevations, higher landscape positions, more acidic bedrock geology, and well-drained soils are associated with lower values of the aforementioned soil variables. Acidity, Al, and Fe, however, are higher at higher elevations, higher landscape positions, more acidic bedrock geology, and well-drained soils.

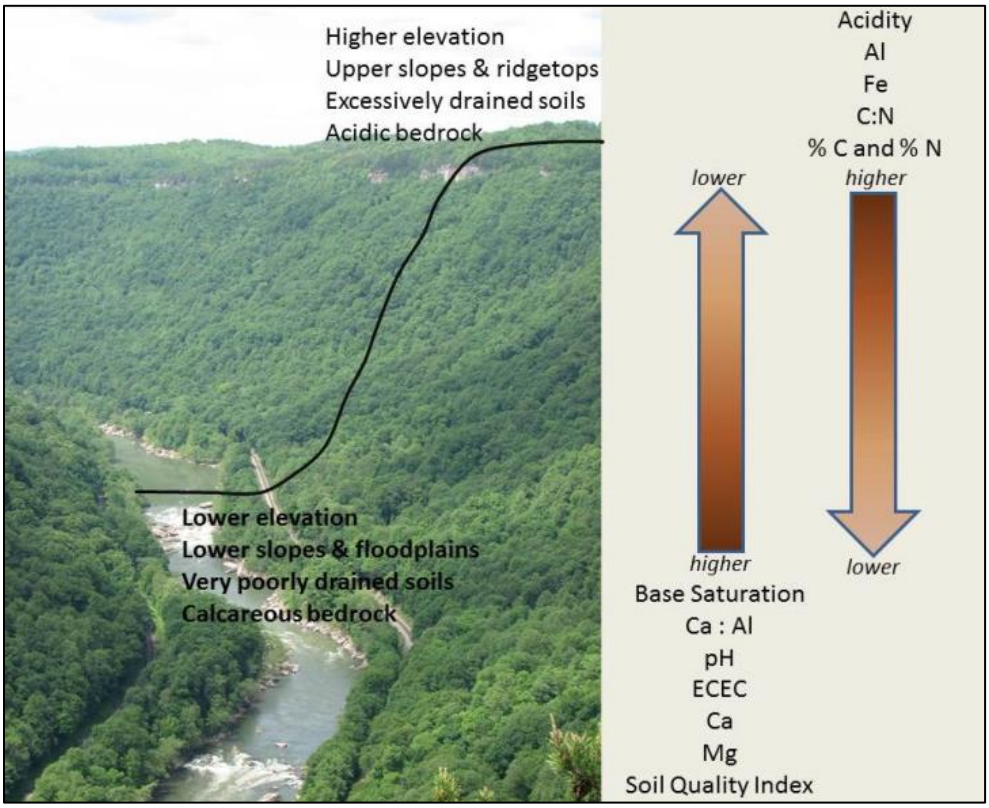


Figure 4. Conceptual diagram of the relationships among elevation, landscape position, bedrock geology and key soil variables.

These patterns can be seen in both the O horizons and the A horizons, although the patterns appear stronger in the A horizons (Appendix B, C, D, and E). This is expected, as chemical properties of the O horizons and A horizons are determined by different soil processes. The strong influence of plant species-specific leaf litter, microbial populations, and other micro-site conditions on O horizon soils may obscure relationships between environmental variables and soil chemical properties. A horizon soils are influenced more strongly by site conditions and the interactions between environmental conditions, biotic, and abiotic factors.

Based on examination of the soil chemical data by parent material and soil taxonomy, soils on floodplains and the terraces adjacent to major rivers are distinctly different than soils in other parts of the parks. These differences are especially apparent in FRHI, DEWA, NERI, and BLUE. This may be due to the intense mixing of parent materials deposited as alluvial material.

Parent material is the geologic material from which soil horizons form, and often provide information on the mode of transport which brought the soil to a particular locale. Soil surveys from ERMN parks include numerous types of parent material:

- Alluvium – transported by streams overflowing their banks;
- Colluvium – transported downslope by the force of gravity and/or erosion;
- Glaciofluvial – transported by moving water from melting ice;
- Residuum – soils formed in place from the weathering of rock;
- Fill – transported recently by humans; and/or
- Till – deposited by glacial ice.

In examining the soil chemical data by parent material, only alluvial soils showed marked differences from other parent material types. Alluvial deposits occur on floodplains and terraces surrounding rivers. Soils from plots on alluvium have higher percent base saturation, pH, Ca:Al ratio, and soil quality index in both the A horizons and O horizons than observed in soils from other parent materials (Figure 4). Acidity, Al, C:N ratio, % LOI, % Carbon, % Nitrogen, P, K, Fe, and Mn were lower in A and O horizon soils from alluvium than from other parent materials (Figure 4).

We examined the soil chemical data by Order, Suborder, and Great Group. No differences were observed in the soil chemical data by Suborder or Great Group. Of the five soil Orders represented in our data (Alfisol, Entisol, Inceptisol, Mollisol, and Ultisol), Mollisols showed distinct differences from the other soil orders. Mollisols occurred in six plots in the floodplain of the New and Bluestone Rivers. In general, Mollisols contain nutrient-enriched A horizons resulting from the long-term addition of organic material and fine sediments during reoccurring flood events. Samples from ERMN Mollisols had higher pH, Ca:Al ratio, base saturation, Ca, and soil quality index than soils in other orders in O and A horizons. These Mollisol samples also had lower acidity, Al, Fe, and Mn in the A horizon than other soil orders. These differences are expected, and, in part, characterize soils as Mollisols.

Soil Acidification

The influence of elevation, landscape position, bedrock geology, and soil drainage on soil chemistry has implications for forest health. For example, when base saturation in the soil drops below 20%, the strong acids in air pollution cause Al to leach into soil water and convert Al into forms that are toxic to terrestrial and aquatic life (Cronan and Schofield 1990). Table 4 shows the percentage of monitoring plots in which A horizon base saturation was below 20% by geology and landscape position group. At upper landscape positions over acidic rocks, 60% of the monitoring plots have base saturation below 20%, whereas only 5% of plots at lower landscape positions over calcareous rocks have base saturation <20%. Thus, in ERMN parks, the forests that are most at risk of negative effects of acid deposition are the forests on ridgetops and upper slopes over acidic bedrock.

Table 4. Percentage of monitoring plots in which A horizon soil base saturation was below 20%.

		Bedrock Geology (Rank)		
		More Acidic (<4)	**Moderate Acidity (4–6)**	**Less Acidic (>6)**
Landscape Position	**Upper**	60	44	23
	Middle	30	30	7
	Lower	14	12	5

Soil Nitrification

One relative indicator of the amount of nitrification occurring in soil is the ratio of carbon to nitrogen (C:N). In general, as C:N ratio decreases, the amount of nitrate that is exported from the soil increases. However, nitrification increases sharply when C:N ratio decreases below 20–25 (Aber et al. 2003). In forested systems with soil C:N ratio below 20, additional nitrogen inputs or disturbance to the soil are likely to lead to further nitrate leaching into streams and rivers.

The C:N ratio in ERMN park soils is influenced by geology, landscape position, and soil drainage class (Appendix B, C, and E, Figure 4). No patterns were observed between the carbon and nitrogen variables and aspect, slope, sulfur deposition, or nitrogen deposition. A strong relationship was not observed between elevation and the carbon and nitrogen variables (Appendix D), probably because the absolute elevation (meters above sea level) is less important within the network than the landscape position (a proxy for relative elevation) of a site. Lovett et al. (2002) reported a weak relationship between C:N ratio and elevation in a forested watershed in the Catskill region of New York, but elevation was less influential on C:N ratio than tree species composition.

In general, plots on upper slopes and ridgetops had higher C:N ratio in the O and A horizons than plots at lower elevations on low slopes and floodplains. Well-drained soils and soils over acidic bedrock (which tend to occur at higher elevations) had higher C:N ratio in the O and A horizons than poorly drained soils and soils over calcareous bedrock (which tend to occur at lower elevations).

Therefore, in ERMN parks, the forests that are more at risk for nitrogen saturation and the subsequent negative consequences are at lower slopes, over more calcareous rock, and are more poorly drained. This is opposite from acidification risk that more strongly affects the higher slopes, acidic rock, and well-drained soils. The higher C:N ratios may not be caused directly by the site factors studied, but may be influenced by tree species composition, land use history, and previous disturbance regimes. Sugar maples tend to be more abundant on the lower mesic slopes; whereas oaks tend to be more abundant on the upper drier slopes, which may influence the C:N ratio (Goodale and Aber 2001).

Park-Specific Results

Important differences in soil chemical properties were observed among ERMN parks. Boxplots of soil chemical properties by park are shown in Appendix F. In general, soils in ALPO and JOFL had higher levels of acidity, Al, Fe, C, and N; and lower base saturation, pH,and Ca:Al ratio compared with the other network parks. Conversely, soils in BLUE and FRHI tended to have higher base saturation, Ca:Al ratio, pH, Ca, and Mg; and lower acidity, Fe, and Al compared with the other network parks. Soil properties in NERI, GARI, FONE, and DEWA tended to have intermediate values, though different parks showed different trends for each soil variable (Appendix F) such that the generalized concepts shown in Figure 5 do not hold true for every park and every soil variable.

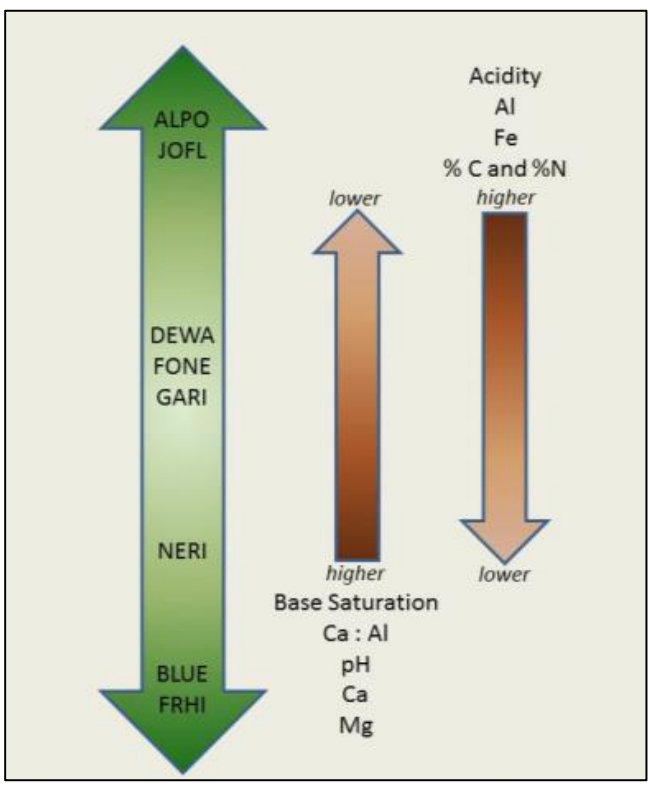


Figure 5. Conceptual diagram for the differences in key soil properties observed among network parks.

These differences are caused by the calcareous-influenced bedrock underneath BLUE and FRHI that leads to richer soils with more buffering capacity against acidic deposition. Also, ALPO and JOFL occur at higher elevations and in areas of higher deposition of sulfur and nitrogen, which may be contributing to the observed soil properties.

Here we present the six main soil indicators on which ERMN will focus for long-term soil monitoring: base saturation, Ca:Al ratio, Al, pH, ECEC, and C:N ratio. In addition, soil zinc concentration is also discussed.

Base Saturation

When base saturation in the soil drops below 20%, the strong acids in air pollution cause Al to leach into soil water and convert Al into forms that are toxic to terrestrial and aquatic life (Cronan and Schofield 1990). Using base saturation as an indicator of risk to forest health (Figure 6), one third of the plots in DEWA and FONE have base saturation less than 20%, and one half of JOFL plots have <20% base saturation. Based on these results, large portions of those parks may be poorly buffered against acidic deposition. In contrast, only five percent of plots in BLUE and FRHI have base saturation <20%.

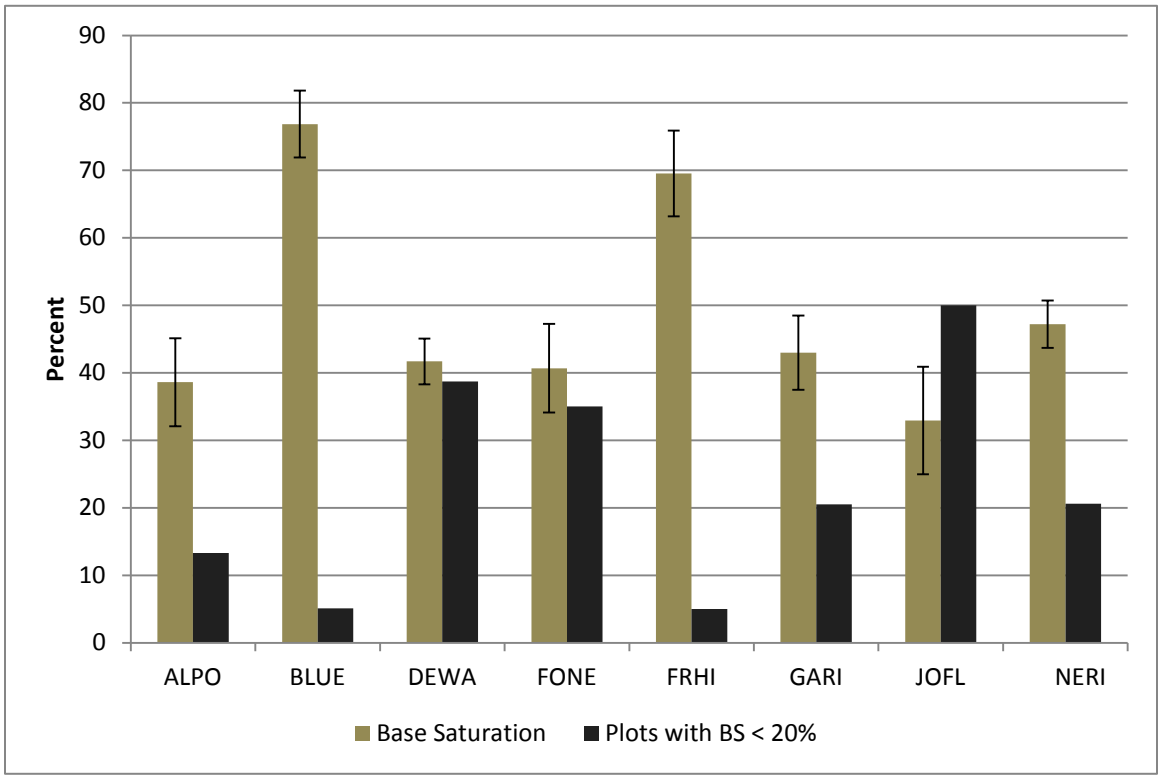


Figure 6. Average (+/- standard error) percent base saturation in A horizon soils and the number of plots with base saturation less than 20% in Eastern Rivers and Mountains Network parks.

Calcium and Aluminum

One of the most frequently cited indicators of forest soil health is the molar ratio of calcium to aluminum (Ca:Al); however, the application of this indicator to forest soil data is complex. For a detailed discussion of the application of Ca:Al ratio as an indicator of forest health to ERMN soil data, see Appendix G. The ERMN will monitor trends in Ca:Al ratio as an index of soil condition, in conjunction with the suite of other variables related to soil condition presented in this report.

Figure 7 shows average Ca:Al ratio and Al concentration by park. Parks such as JOFL, ALPO, and FONE, with low Ca:Al ratio, tend to have high Al concentrations which may be toxic to plants and aquatic systems. BLUE and FRHI have higher average Ca:Al ratio and lower Al concentrations due to the richer soils derived from calcareous-influenced bedrock found in these parks.

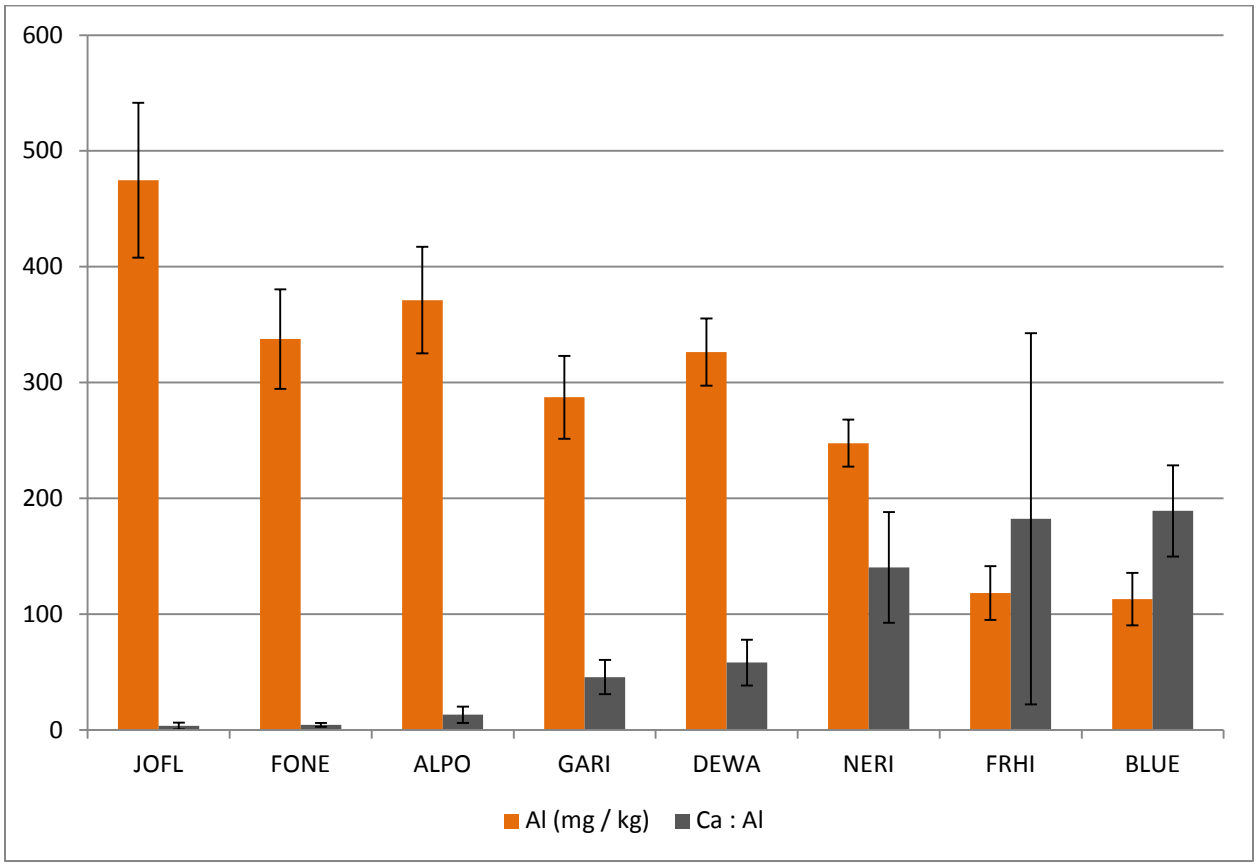


Figure 7. Average (+/- standard error) Ca:Al ratio and Al concentration in A horizon soils in Eastern Rivers and Mountains Network parks.

Acidity and Acid Neutralization Potential

The pH of most forest soils in ERMN parks ranges from 4–6, typical of eastern forest soils (Figure 8). In general, soil pH in ALPO, JOFL, and DEWA are lower, and soil pH in BLUE and FRHI are higher than in the other network parks. Average ECEC shows a slightly different pattern, with ALPO, BLUE, and JOFL showing the highest average ECEC and FONE, FRHI, and GARI showing the lowest ECEC (Figure 8).

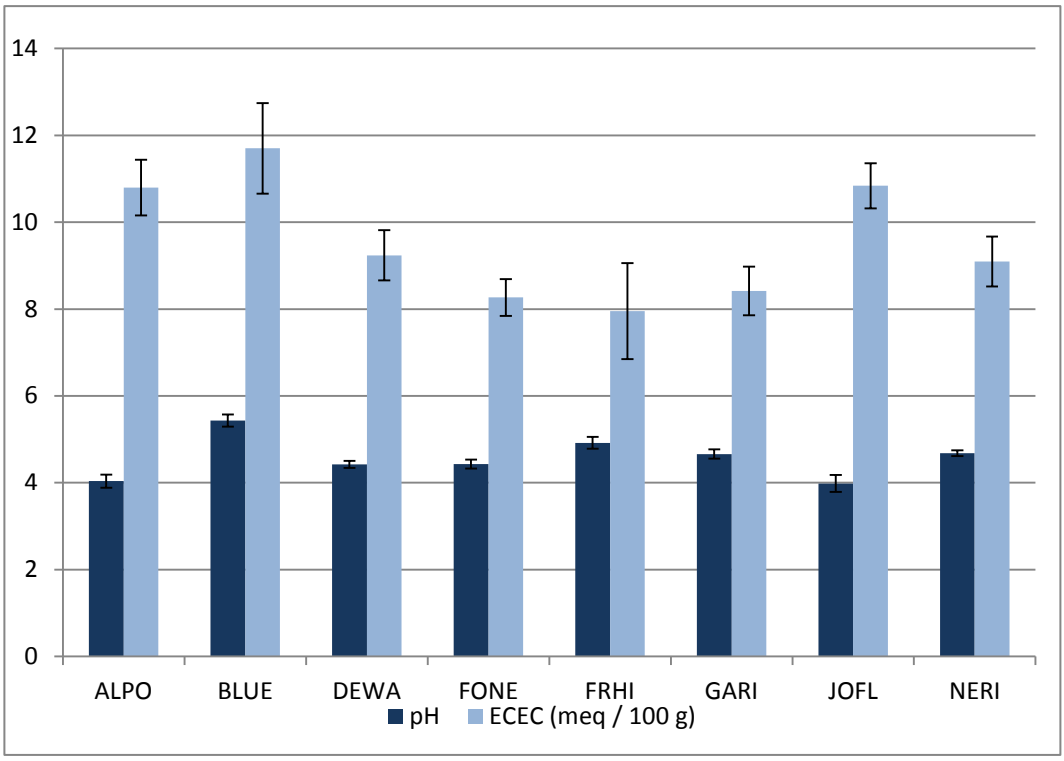


Figure 8. Average (+/- standard error) pH and ECEC in A horizon soils in Eastern Rivers and Mountains Network parks.

Carbon and Nitrogen

One relative indicator of the amount of nitrification occurring in soil is the ratio of carbon to nitrogen (C:N ratio). In general, as C:N ratio decreases, the amount of nitrate that is exported from the soil increases; however, nitrification increases sharply when C:N ratio decreases below 20–25 (Aber et al. 2003). In forested systems with soil C:N ratio below 20, additional nitrogen inputs or disturbance to the soil are likely to lead to further nitrate leaching into streams and rivers.

Differences were observed in average C:N ratio among the parks (Figure 9). In all parks, at least half the plots had C:N ratio less than 20, indicating that nitrification is a concern in parts of all network parks. ALPO had higher A horizon C:N ratio than all parks except for BLUE and JOFL. A horizon C:N ratio in FRHI was lower than in most other network parks. Nearly all of the mineral soil sampled in FRHI and FONE had a C:N ratio less than 20, indicating a higher level of nitrification and possible nitrate leaching with potential deleterious effects on water quality. The low C:N ratio at FRHI may be a result of the recent agriculture. Agricultural land use history is associated with lower C:N ratio, often from the loss of carbon from tillage and the additional inputs of nitrogen (Verheyen et al. 1999, Murty et al. 2002). Agricultural soils are also dominated by bacteria rather than fungi, which is associated with lower C:N ratios. However, FONE forests do not have the same recent agricultural history, yet FONE soils also exhibit a low average C:N ratio, possibly a result of tree species composition (Goodale and Aber 2001) or other environmental factors.

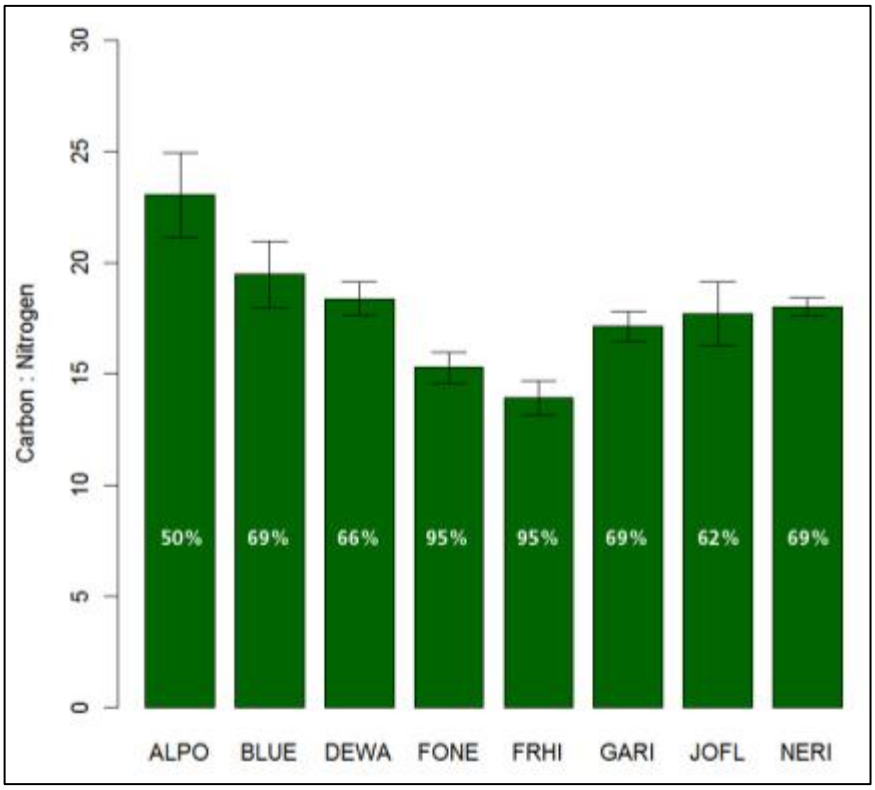


Figure 9. Average (+/- standard error) carbon to nitrogen ratio for mineral soil sampled in Eastern Rivers and Mountains Network parks. Percentages shown on bars are percentage of monitoring plots in which mineral soil C:N ratio was below 20.

Soil Zinc Concentration

Zinc (Zn) concentration in soil samples varied widely among ERMN parks (Figure 10). Zn concentration in O and A horizon samples was much higher in DEWA than in all other parks. A horizon Zn concentrations were significantly higher in JOFL than in the three West Virginia parks.

One source of the Zn in the DEWA soils could be the former zinc smelting operation in Palmerton, PA, which is approximately 30 miles southeast of the park's southern boundary. For nearly 70 years, the New Jersey Zinc Company smelting operations emitted huge quantities of heavy metals. As a result, approximately 2,000 acres on Blue Mountain, which is adjacent to the former smelters, have been completely defoliated. Attempts to remediate and revegetate the contaminated area began in 1987 and are ongoing today.

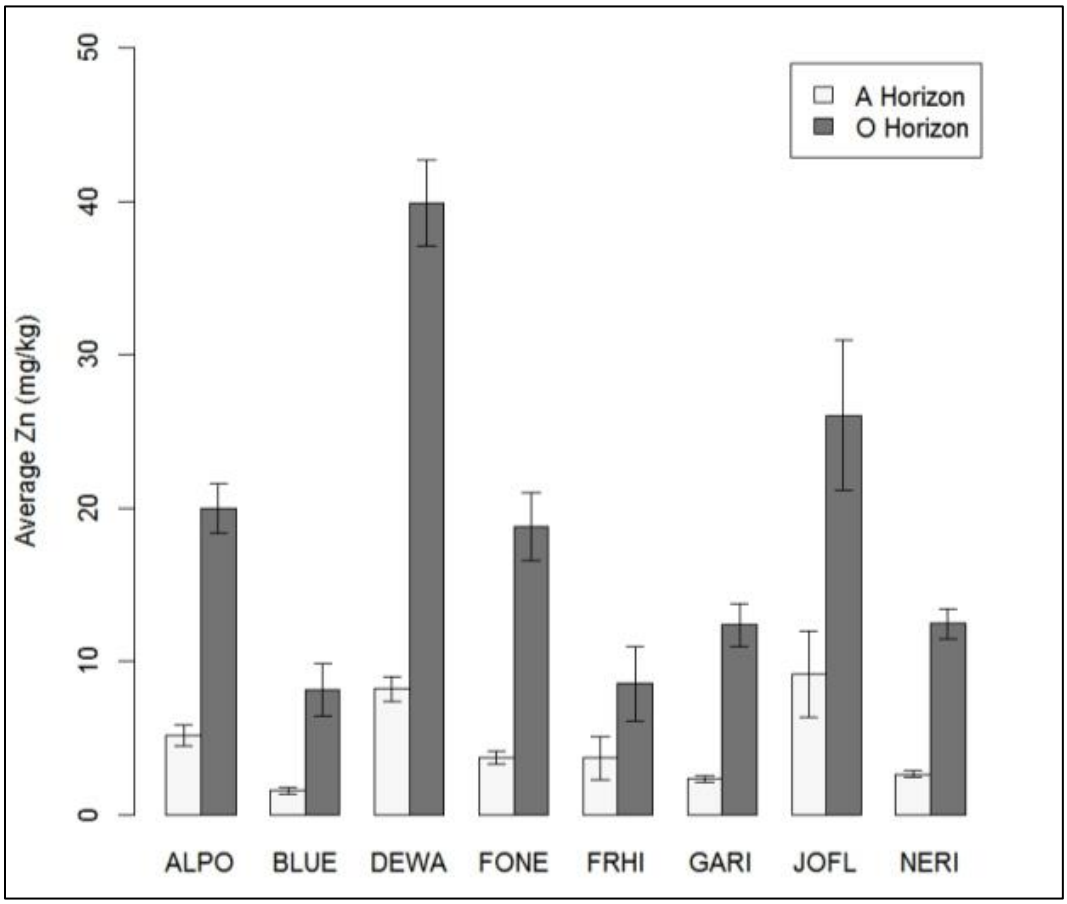


Figure 10. Average (+/- standard error) zinc concentration for soil sampled in Eastern Rivers and Mountains Network parks.

Discussion

Soil samples collected at long-term forest health monitoring plots in ERMN parks provide important information on the status of the parks' soil resources. These data indicate that park soils are following region-wide trends with respect to S and N deposition and soil condition.

Within ERMN parks, geology group, landscape position group, elevation, and soil drainage class strongly influence the forests' vulnerability to acidification. Well-drained soils over acidic bedrock on upper slopes and ridgetops support forests that are more at risk of deleterious effects of acidic deposition because they have depleted nutrients, less buffering capacity, and higher concentrations of aluminum that can be toxic to plants. Forests on lower slopes, more calcareous bedrock, and poor drainage are less at risk since these forests tend to have richer soils with more nutrients, more buffering capacity, and lower non-toxic concentrations of aluminum.

These differences are illustrated clearly within DEWA where acidic soils on ridgetops and upper slopes are very susceptible to acidic deposition effects when compared with richer soils that occur in the river valley over limestone bedrock. Similar patterns are observed in NERI and GARI when ridgetop soils are compared with valley soils. Of the ERMN parks, BLUE and FRHI are least vulnerable to acidic deposition because of the calcareous-influenced bedrock that leads to richer soils with more buffering capacity. On the opposite end of the risk spectrum, ALPO and JOFL occur at higher elevations and in areas of high deposition of sulfur and nitrogen, which causes the soil in those parks to be more sensitive to negative effects of acidic deposition.

The C:N ratio in ERMN park soils is also influenced by geology, landscape position, and soil drainage class. In general, soils on upper slopes and ridgetops, over acidic rock and well-drained soils had higher C:N ratios than soils on low slopes and floodplains, poorly-drained soils, and soils over calcareous bedrock (which tend to occur at lower elevations). Contrary to our findings, Castellano et al. (2013) reported higher C:N ratios in downslope soils when compared with soils from upper slopes and suggested that N is transported downslope. In ERMN parks, the forests that are more at risk for nitrogen saturation and the subsequent negative consequences are at lower slopes, over more calcareous rock, and on more poorly drained soils. This is opposite from forests that are at high risk from acidification (soils on the higher slopes, acidic rock, and well-drained soils). However, the C:N ratios may be more influenced by tree species composition and land use history than by environmental factors explored here.

No patterns were observed in this study between the soil variables and aspect or slope; however, several previous studies in the region have documented important relationships between soil properties, aspect, and slope (Tajchman 1983, Boerner 1984, Hicks and Frank 1984, Elias et al. 2009). Thus, aspect and slope are probably influential on soil properties at the site or park level. From the broad-scale-network perspective, other environmental factors are more influential than aspect and slope.

The exploratory data analyses presented here provide context with which to view ERMN soil monitoring data. These data provide an important baseline with which to analyze trends in soil condition as additional soil samples are collected in the future.

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Appendix A. Geology ranking.

Using the best available digital geologic maps for each park, the bedrock geology mapped underneath each monitoring plot was identified. The resulting 36 different rock types (lithologies) were then ranked on a scale from 1–10 according to the rocks' "acidity" or buffering capacity in relation to acidic deposition (Table 1). Similar ranking systems for geologic units have been developed by Robinson (1997), Connolly et al. (2007), and Anderson and Ferree (2010). Lithologies, such as limestone, known to have substantial sources of alkalinity were assigned higher ranks because the rocks could provide a reasonable level of buffering capacity to the overlying soil. On the other end of the spectrum, lithologies, such as black shales, that contain substantial amounts of pyrite and produce an excess of sulfuric acid as the pyrite breaks down, were ranked at the low end of the scale. Lithologies known to have a moderate amount of alkaline producing minerals or interbedded seams of calcareous materials received an intermediate ranking. This ranking system has several limitations. First, geologic maps are typically coarse-scale, and are not necessarily intended to be applied to an exact location such as a monitoring plot. Second, there is much vertical and horizontal spatial variability within most mapped lithologies. As such, the same lithology may have been assigned a slightly different ranking in different parks due to the known differences in the rocks between the different localities (Table A1). Third, the soil collected in the monitoring plots may not be directly influenced by the underlying bedrock depending on the surficial geologic processes that influenced the area. To account in part for surficial processes, all plots that occurred on alluvium (e.g., active floodplains of large rivers or tributaries) were assigned a rank of 8, regardless of the mapped lithologies. Despite these limitations, we feel this ranking system is a representative and appropriate method of incorporating geologic information into the data analyses.

The numeric ranks were then grouped in three broad categories:

- A = more acidic lithologies (<4)
- B = intermediate lithologies (4–6)
- C = more calcareous lithologies (>6).

Table A1. Ranking of lithologies mapped under monitoring plots in Eastern Rivers and Mountains Network parks.

Lithology	ALPO	BLUE	DEWA	FONE	FRHI	GARI	JOFL	NERI
Allegheny Formation	3.5			3				
Bloomsburg Red Beds			4					
Bluestone Formation								3.5
Bluestone Formation, Pride Shale Member		5.5						
Brallier and Harrell Formations, undivided	2.5							
Burgoon Sandstone	8.5			8.5				
Buttermilk Falls Limestone			8.5					
Buttermilk Falls Limestone through Esopus Formation, undivided			8.5					
Carmichaels					7			
Casselman Formation					6		6	
Catskill Formation	6							
Decker Formation through Poxono Island Formation, undivided			6					
Esopus Formation			5					
Foreknobs Formation	7							
Glenshaw Formation	4.5			5				
Hinton Formation, lower		6.5						
Hinton Formation, middle		6.5						
Hinton Formation, upper		4.5						
Kanawha Formation						5		
Mahantango Formation			3					
Marcellus Shale			2					
Minisink Limestone and New Scotland Formation, undivided			9.5					
Monongahela Group					8.5			
New River Formation						5		3
New River Formation, Lower Nuttall Sandstone						6		
New River Formation, Upper Nuttall Sandstone						5		
Oriskany Group			6.5					
Pocahontos Formation								3
Pottsville Group	4.5							4.5
Poxono Island Formation			8					
Princeton Formation		8.5						
Ramseyburg Member			6					
Rockwell Formation	7.5							
Schoharie Formation			7.5					
Shawangunk Formation			3					
Trimmers Rock Formation			3					

Appendix B. Boxplots for soil variables by geology group.

Using the best available digital geologic maps for each park, the bedrock geology mapped underneath each monitoring plot was identified. The rock types were then ranked on a scale from 1–10 according to the rocks' "acidity" or buffering capacity in relation to acidic deposition (Appendix A). The numeric ranks were then grouped in three broad categories:

- A = more acidic lithologies (<4)
- B = intermediate lithologies (4 – 6)
- C = more calcareous lithologies (>6)

Table B1. The number of monitoring plots per geology group at which soils were collected.

	Geology Group			
Horizon	**A**	**B**	**C**	**Total**
O	106	109	30	245
A	117	147	70	334
Total	223	256	100	

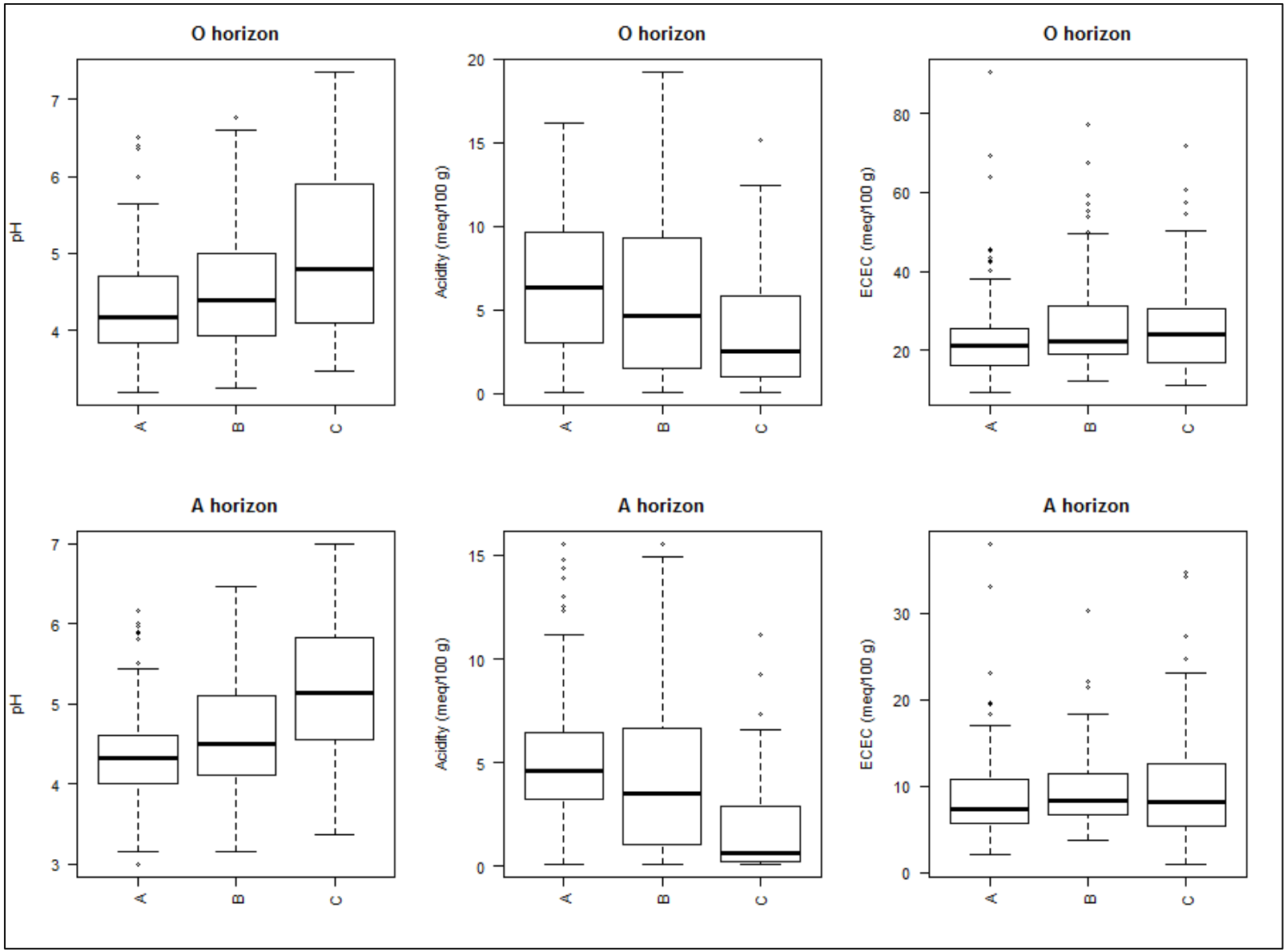

Figure B1. Soil parameters for each geology group by horizon.

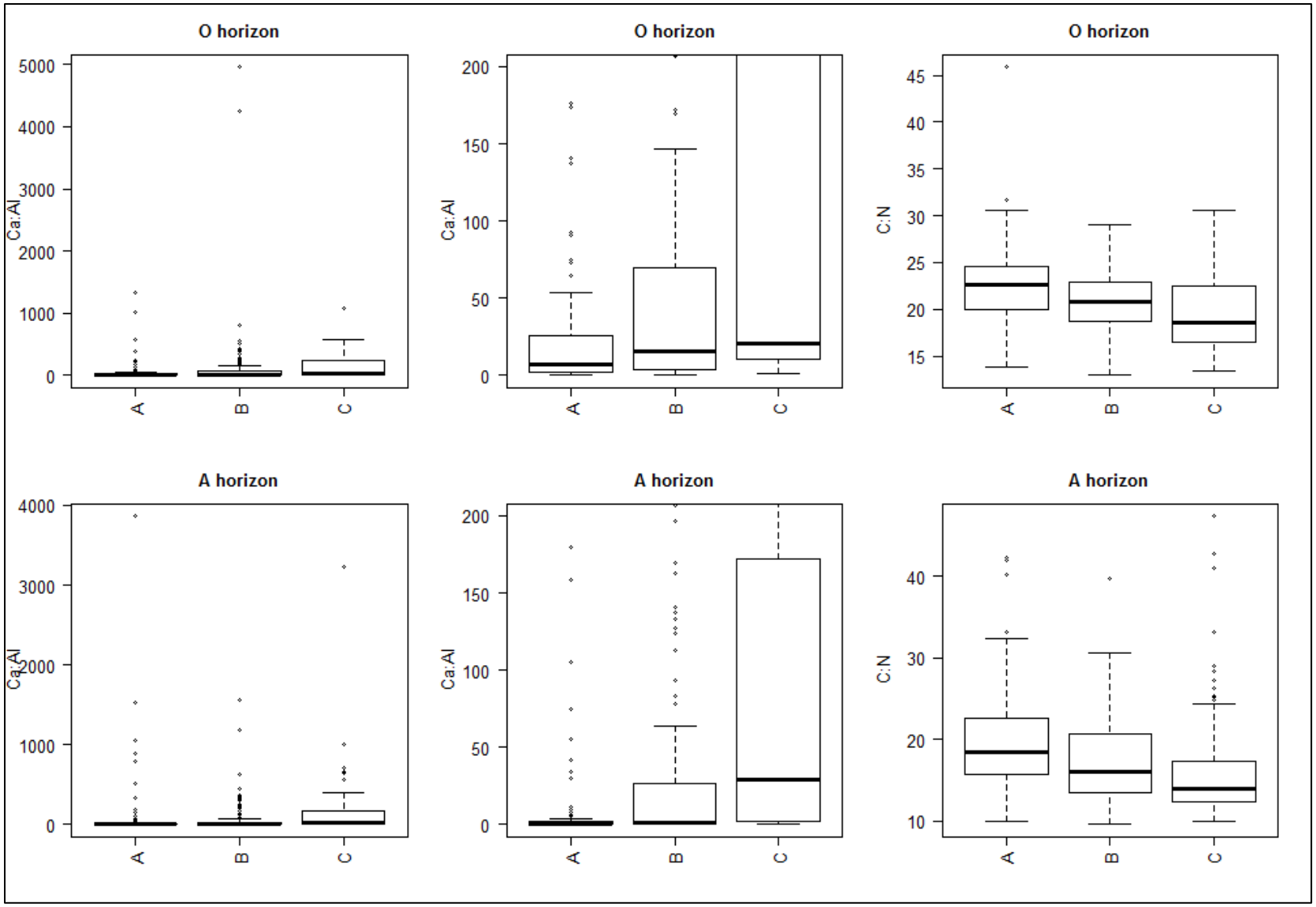

Figure B2. Ca:Al and C:N ratios for each geology group by horizon. The second column of Ca:Al shows the lower range of ratio values for the groups.

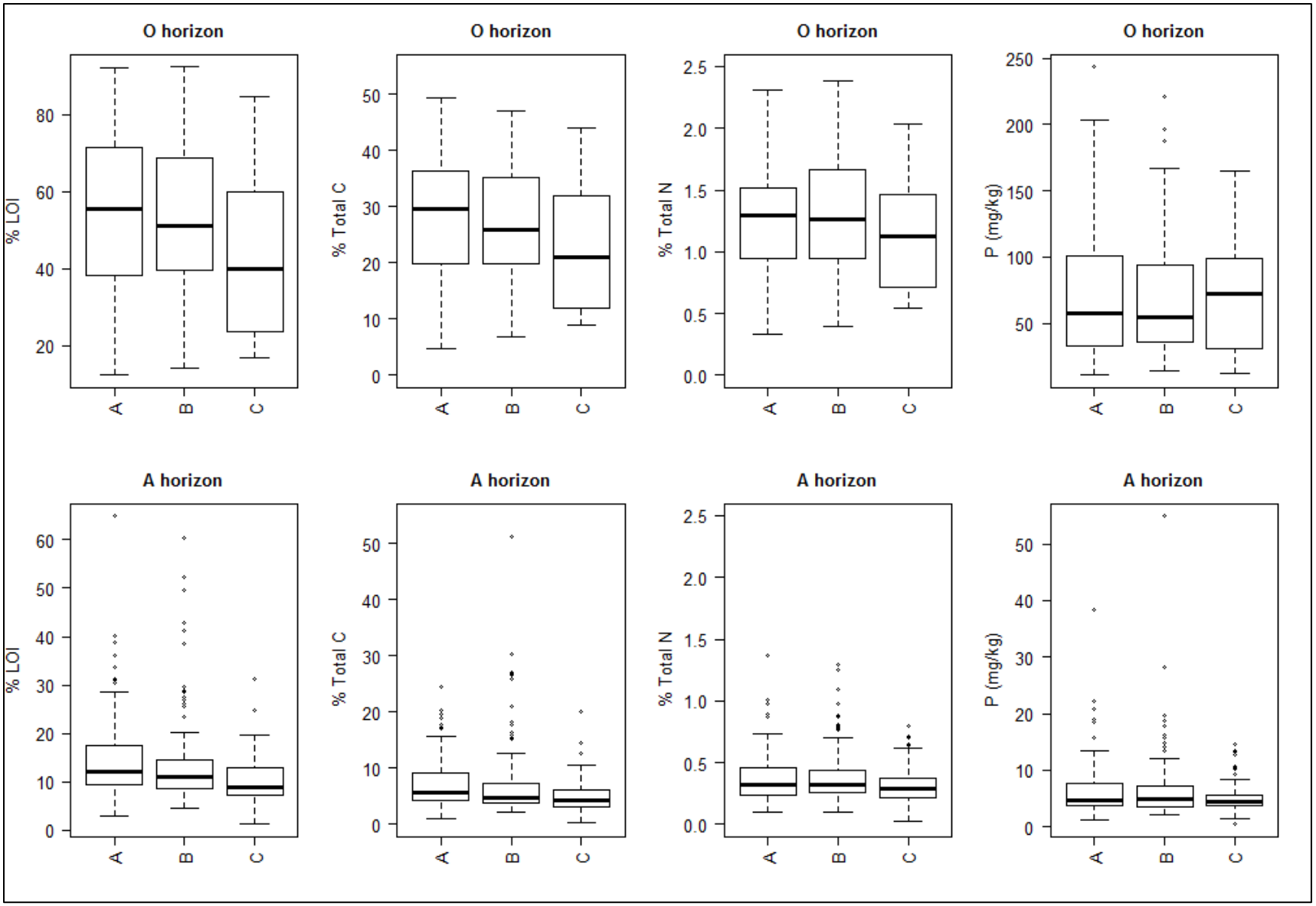

Figure B3. C and N parameters for each geology group by horizon.

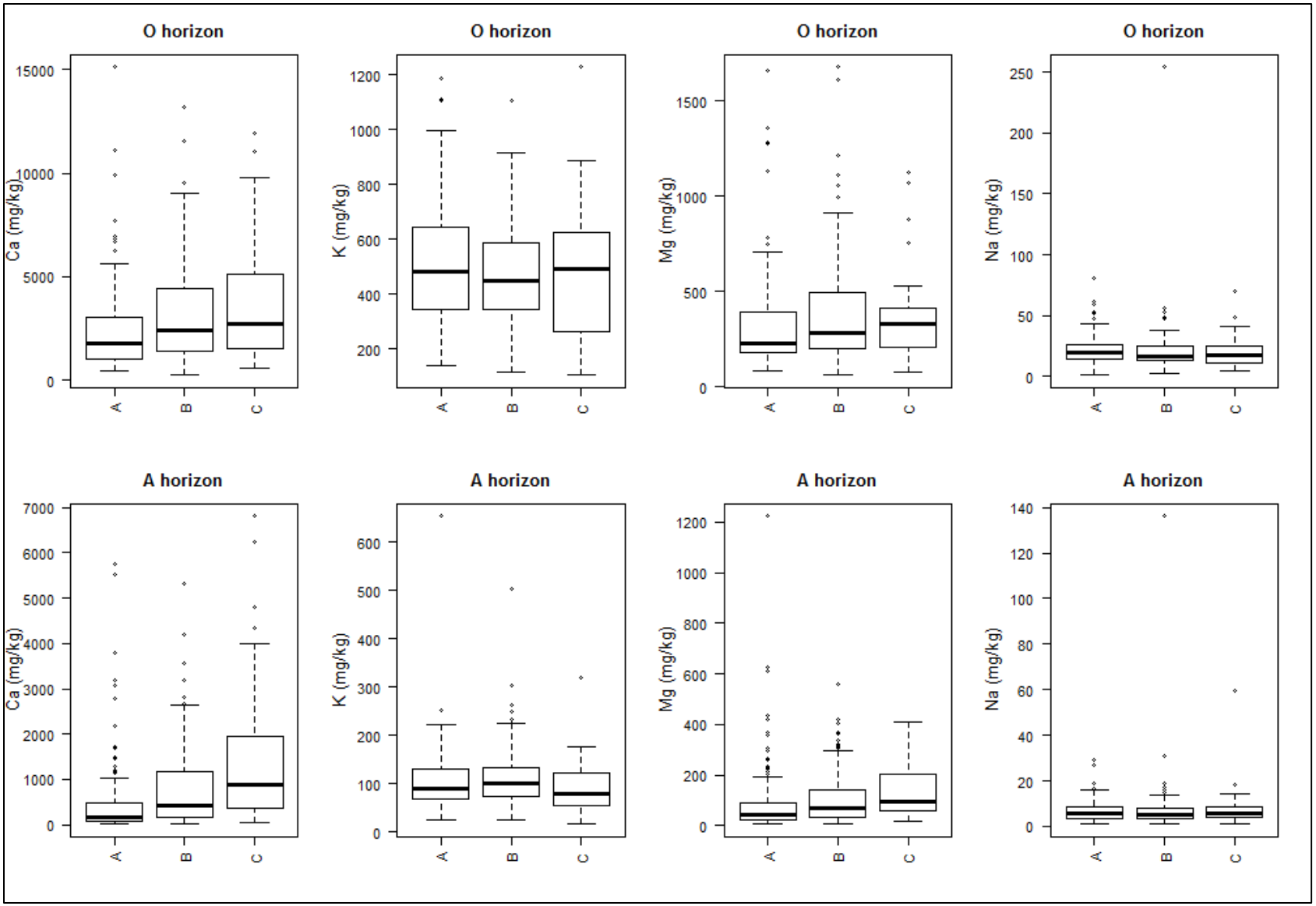

Figure B4. Base cations for each geology group by horizon.

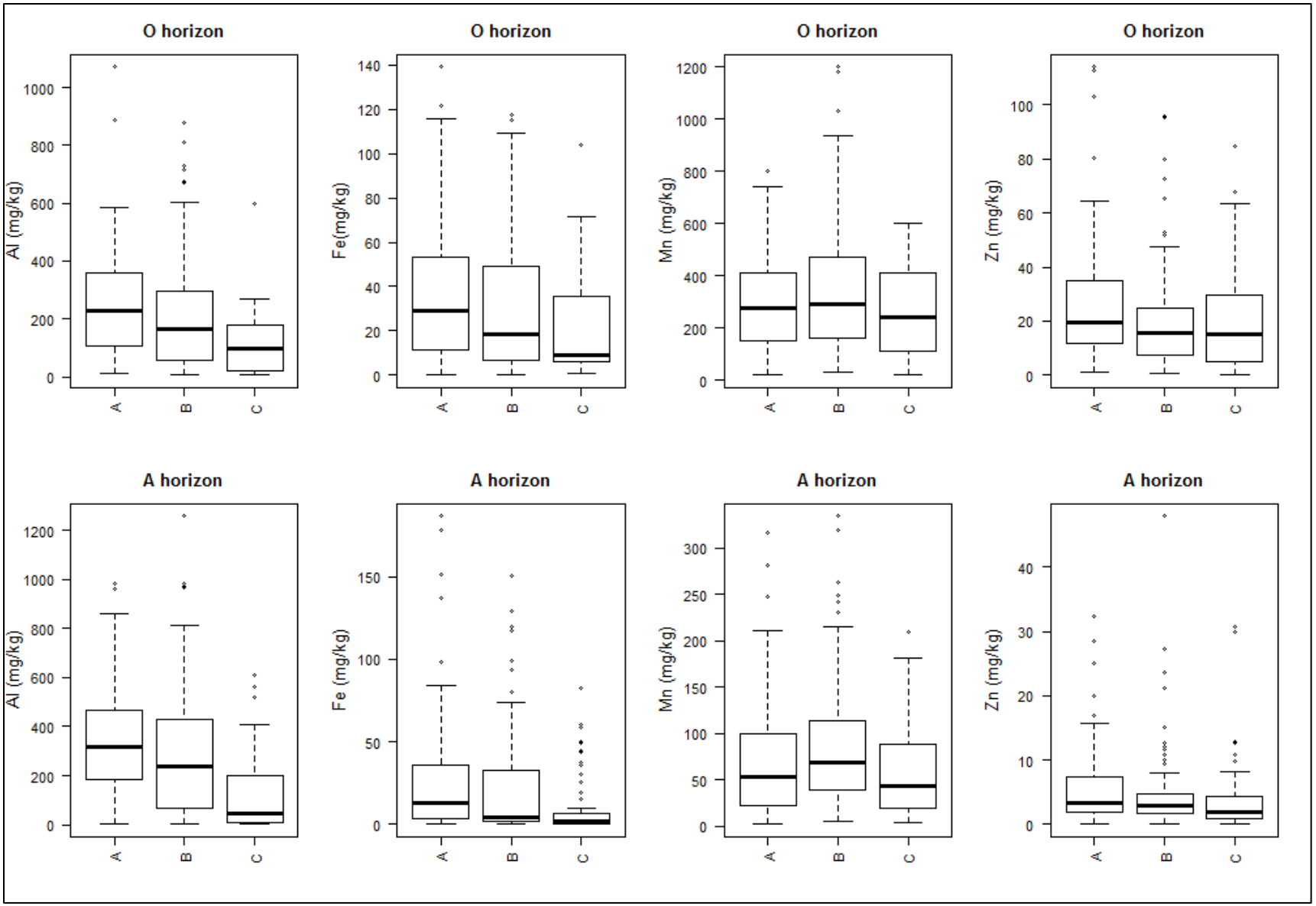

Figure B5. Acid cations for each geology group by horizon.

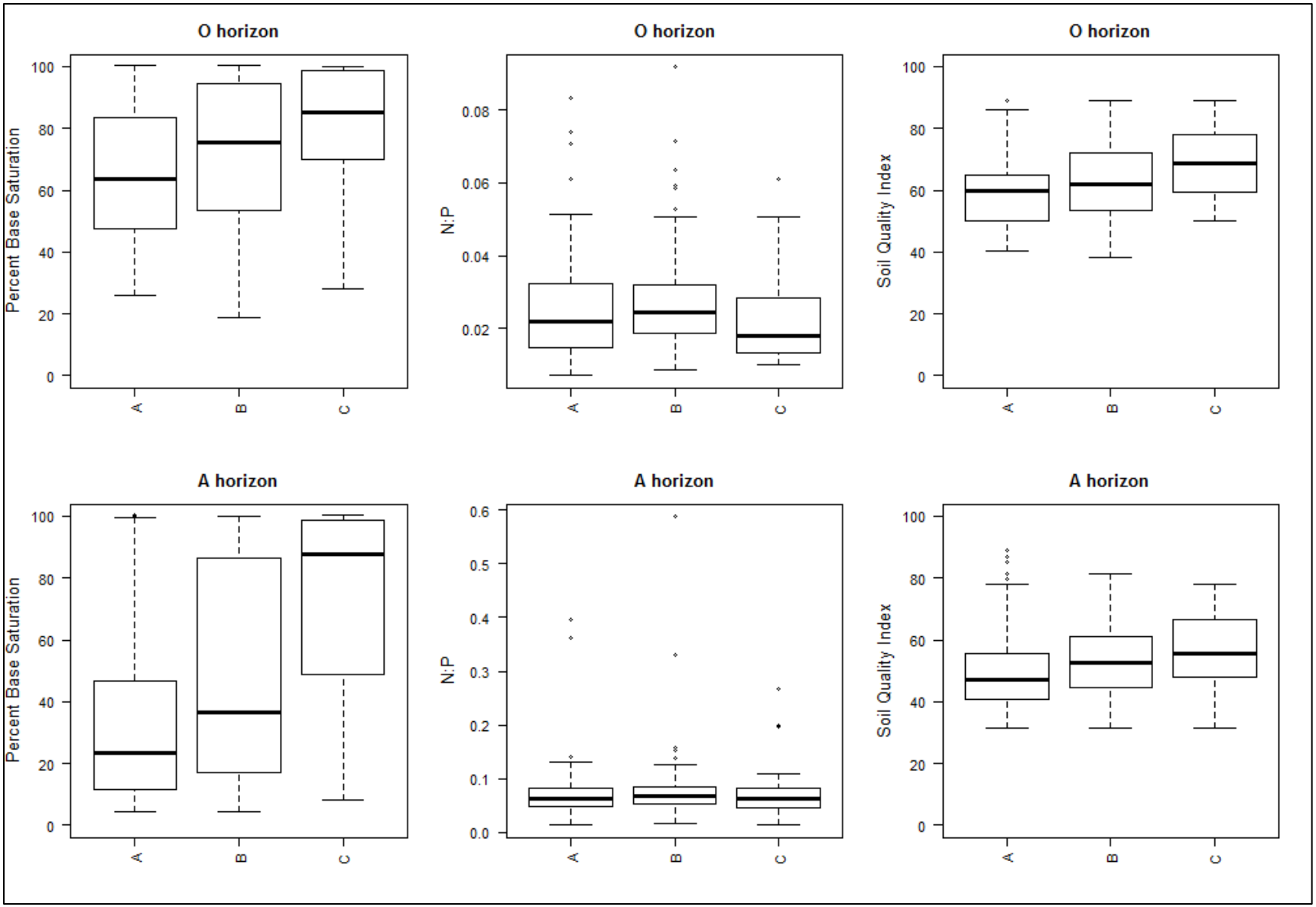

Figure B6. Percent base saturation, N:P and soil quality index for each geology group by horizon.

Appendix C. Boxplots for soil variables by landscape position.

The position of each monitoring plot on the landscape was recorded in the field. The landscape positions were then grouped into three categories:

- Upper = ridgetops and upper slopes
- Middle = midslopes and benches
- Lower = lower slopes, bottomland and floodplains

Table C1. The number of plots per landscape position group at which soils were collected.

	Landscape Position			
Horizon	**Upper**	**Mid**	**Lower**	**Total**
O	125	74	46	246
A	137	93	104	334
Total	262	167	150	

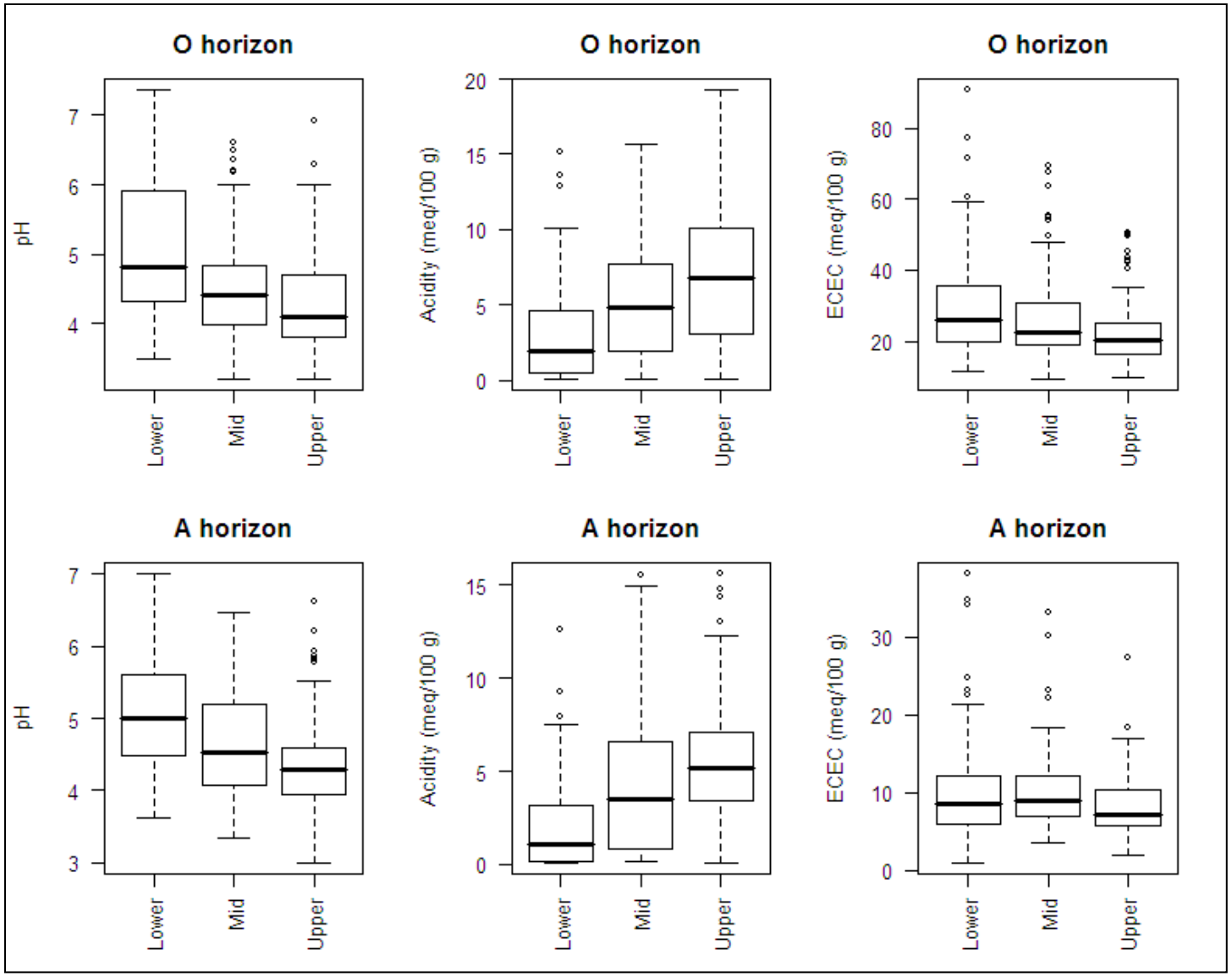

Figure C1. Soil parameters for each landscape position group by horizon.

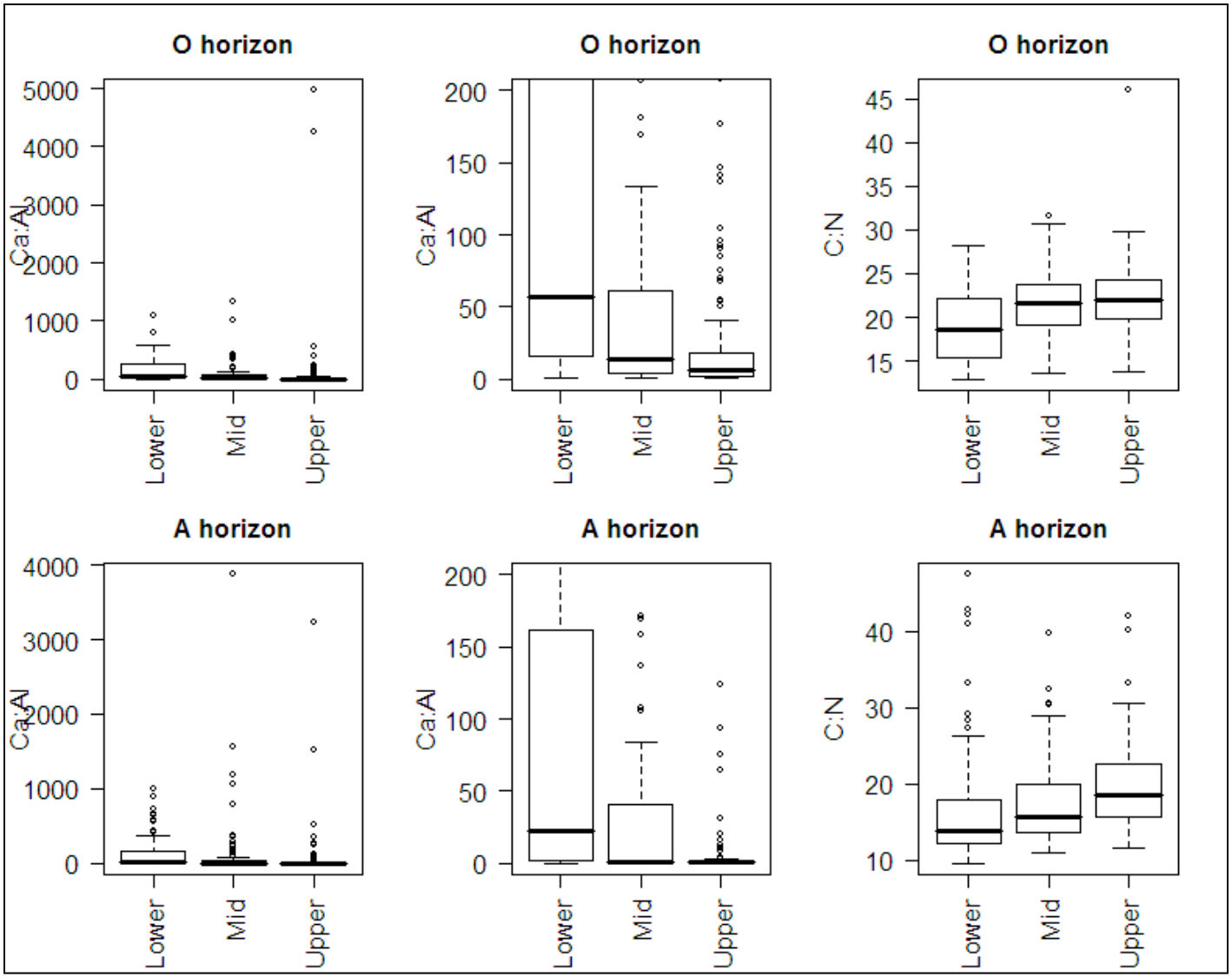

Figure C2. Ca:Al and C:N ratios for each landscape position group by horizon. The second column of Ca:Al shows the lower range of ratio values for the groups.

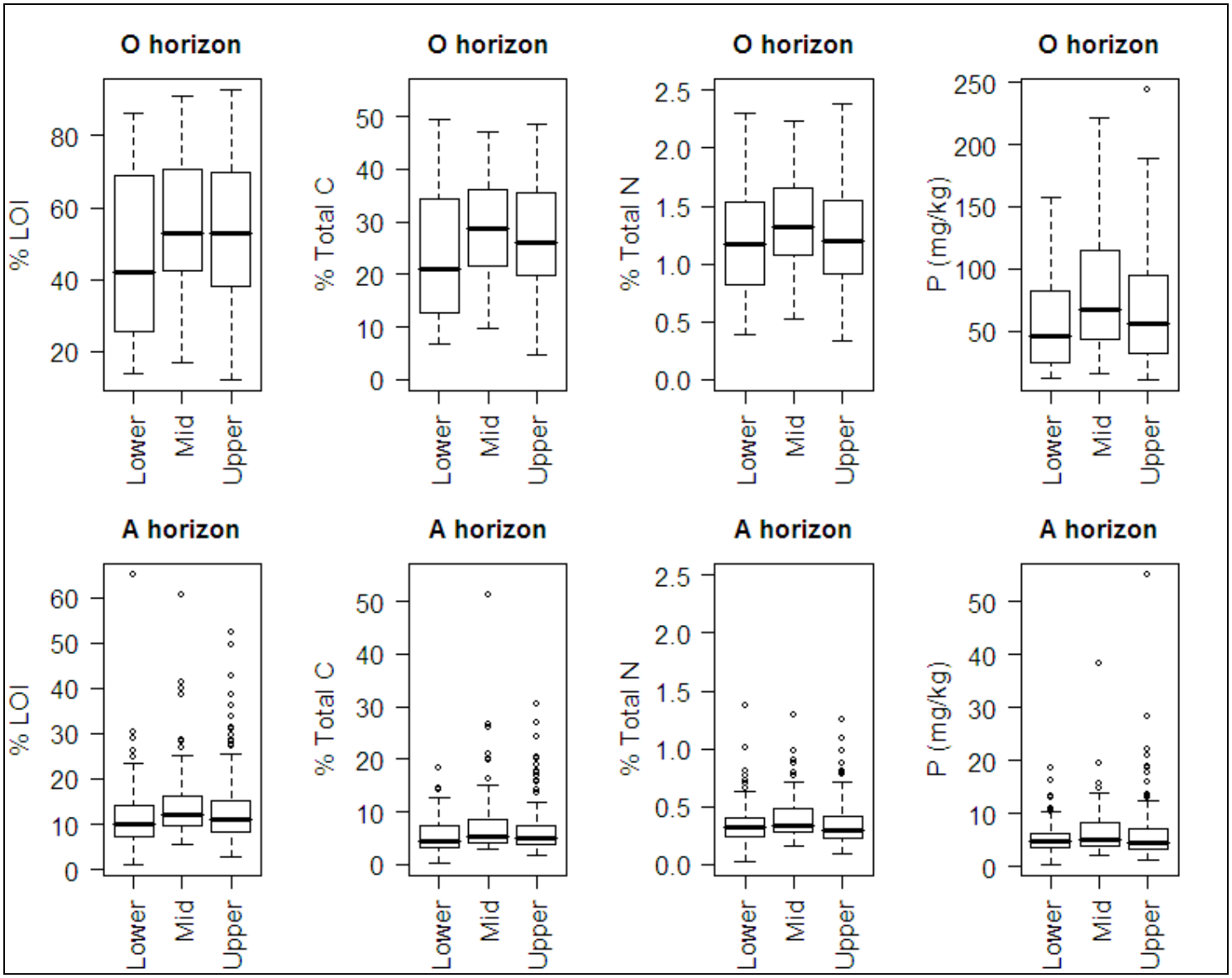

Figure C3. C and N parameters for each landscape position group by horizon.

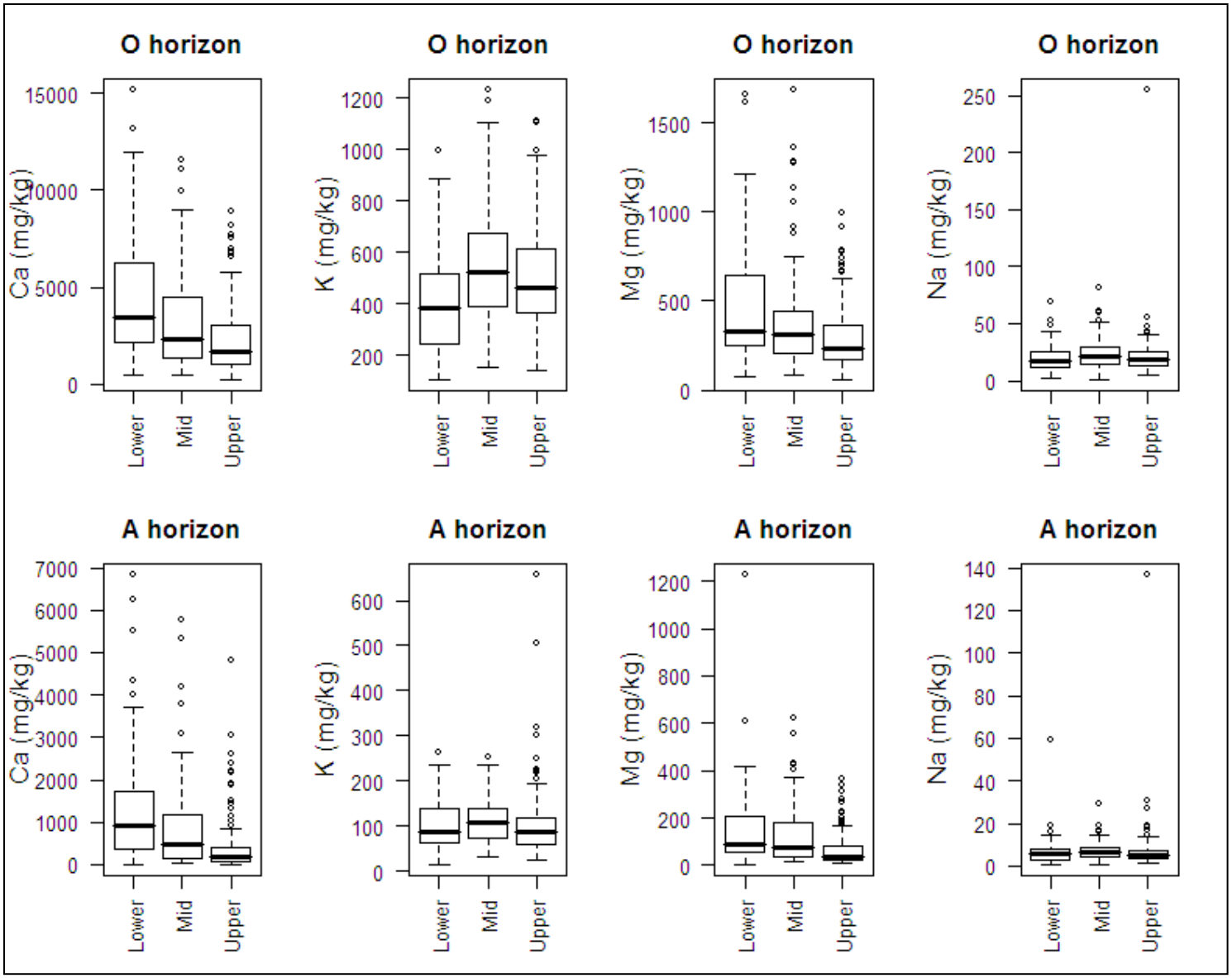

Figure C4. Base cations for each landscape position group by horizon.

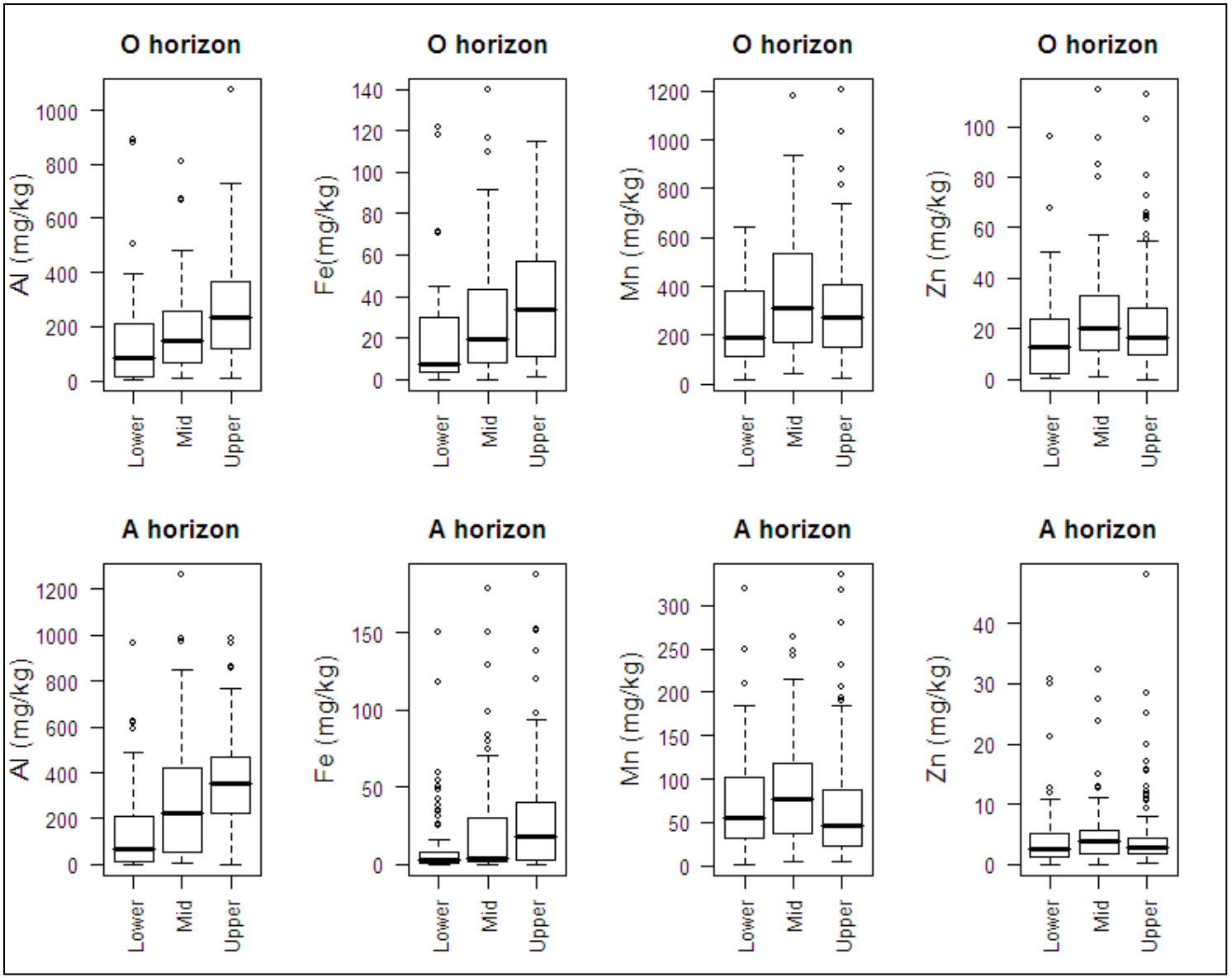

Figure C5. Acid cations for each landscape position group by horizon.

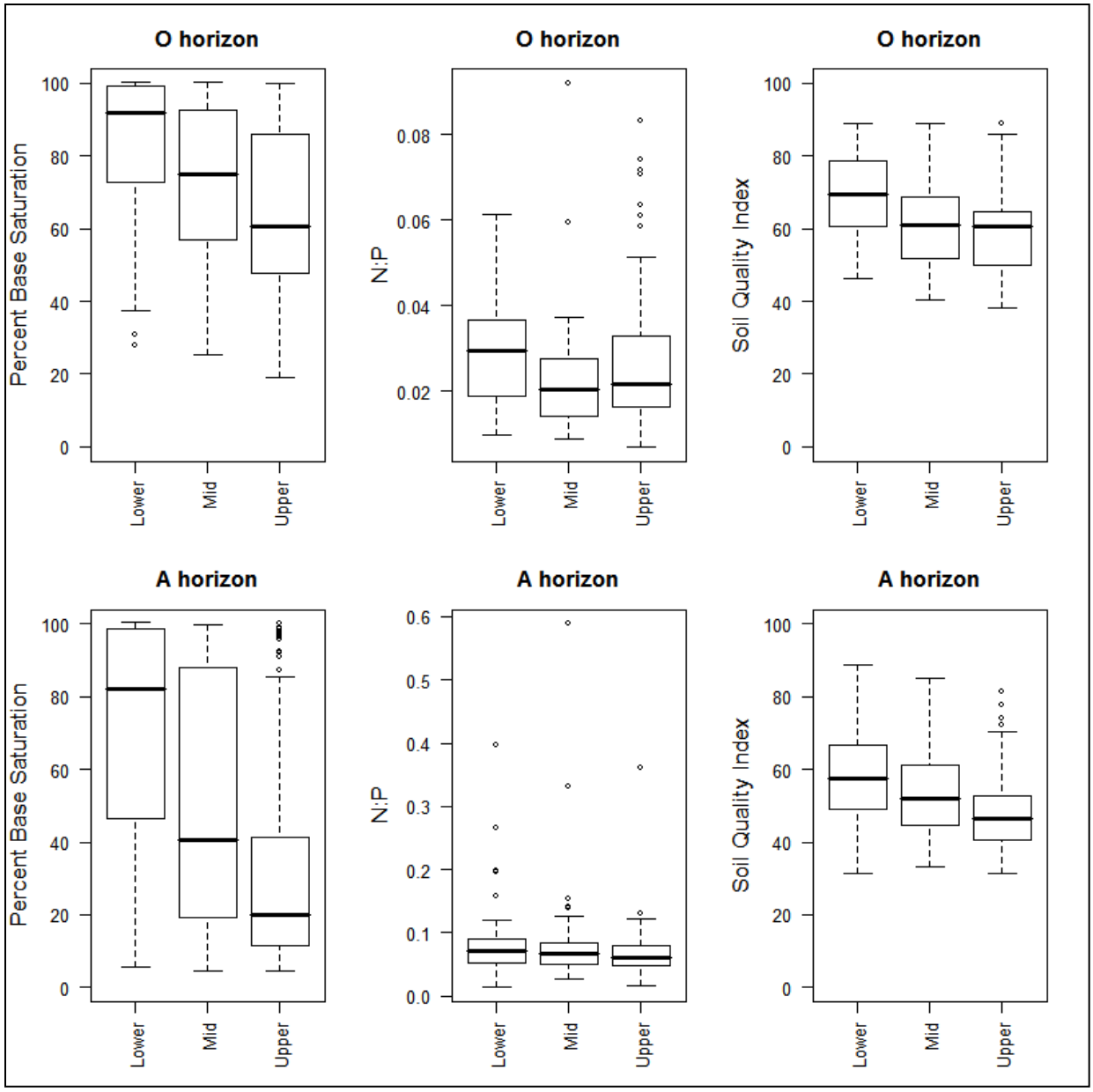

Figure C6. Percent base saturation, N:P and soil quality index for each landscape position group by horizon.

Appendix D. Scatterplots for soil variables and elevation.

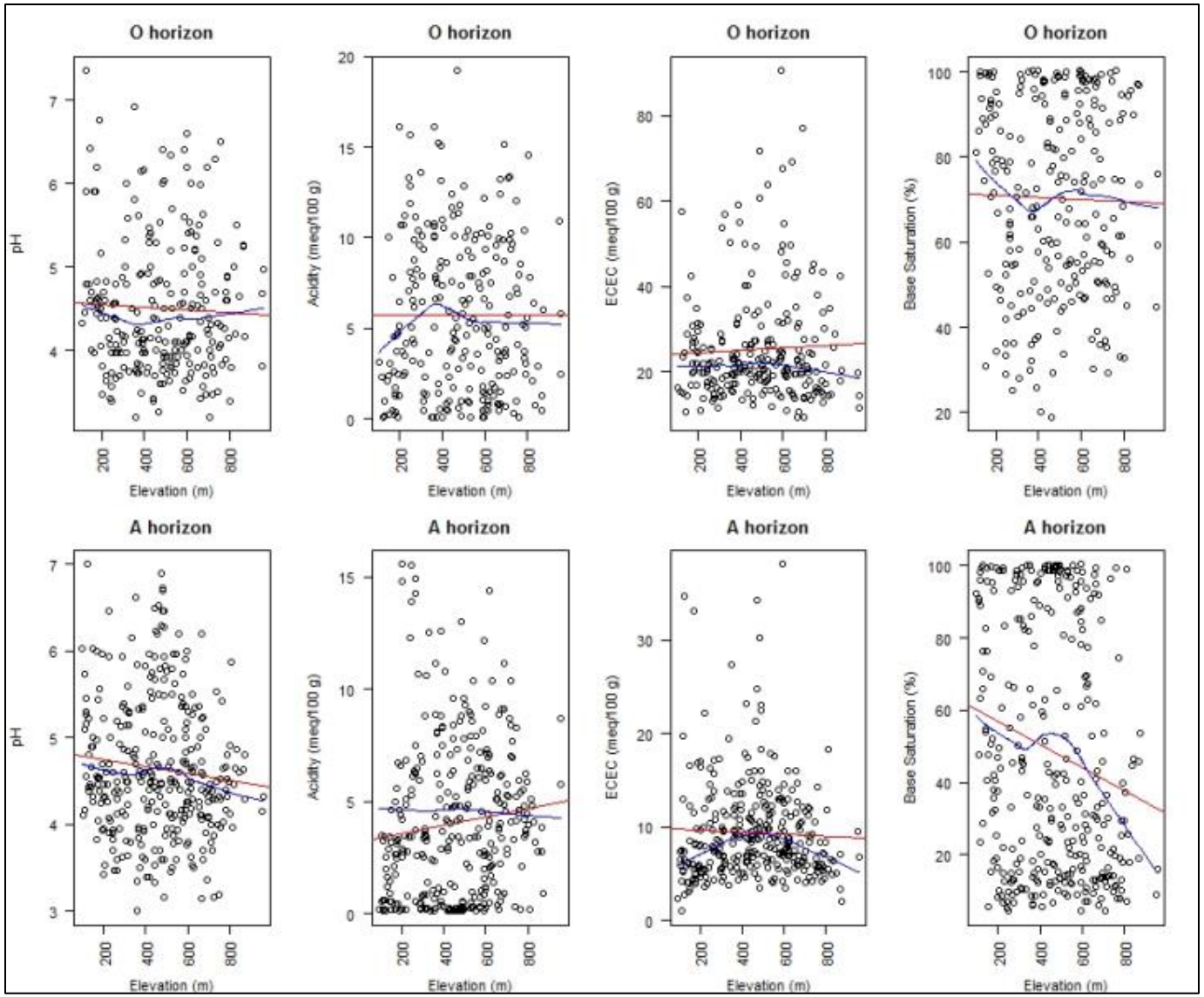

Figure D1. Soil parameters plotted against elevation of monitoring plot. Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in blue.

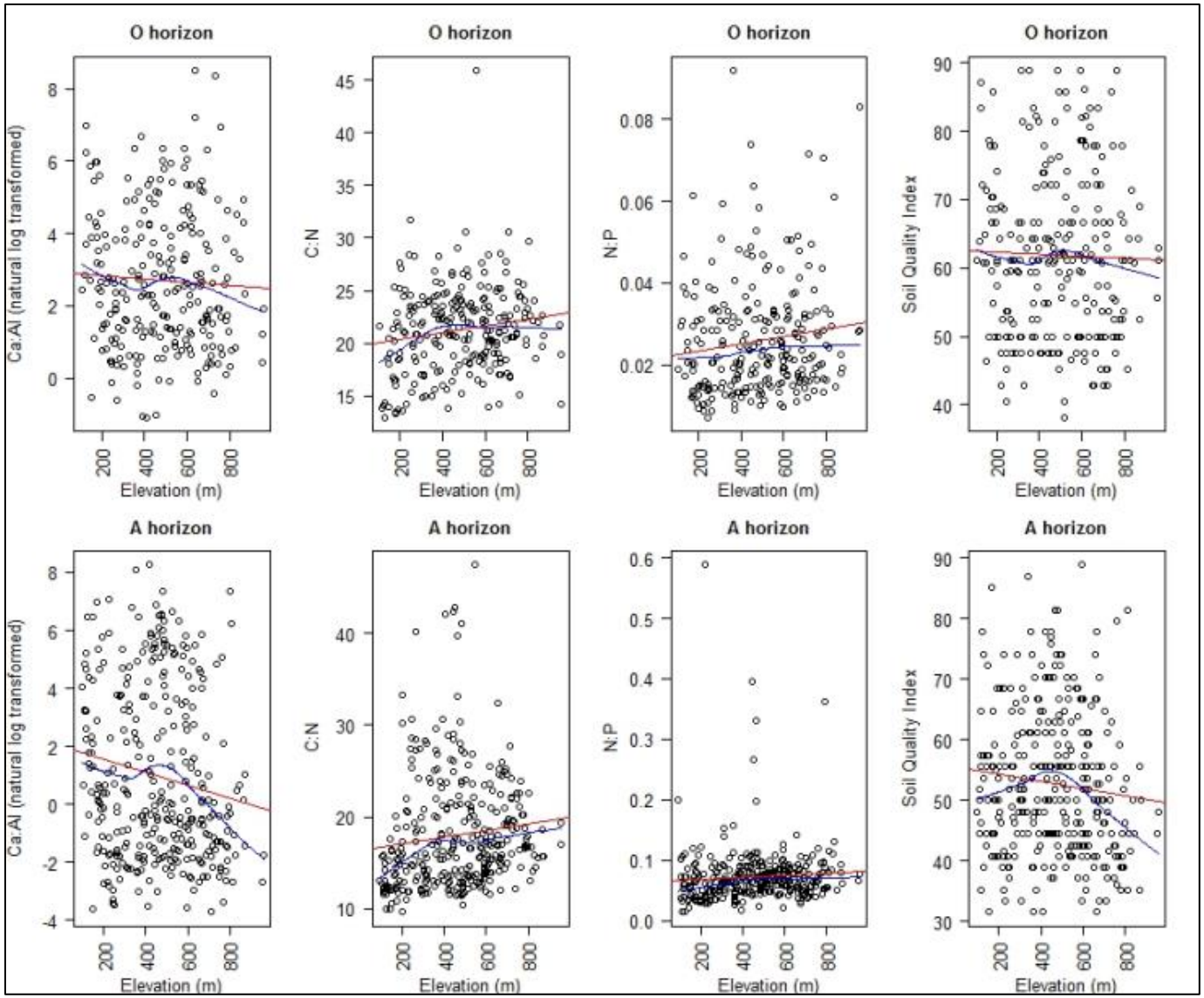

Figure D2. Soil parameters plotted against elevation of monitoring plot. Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in blue.

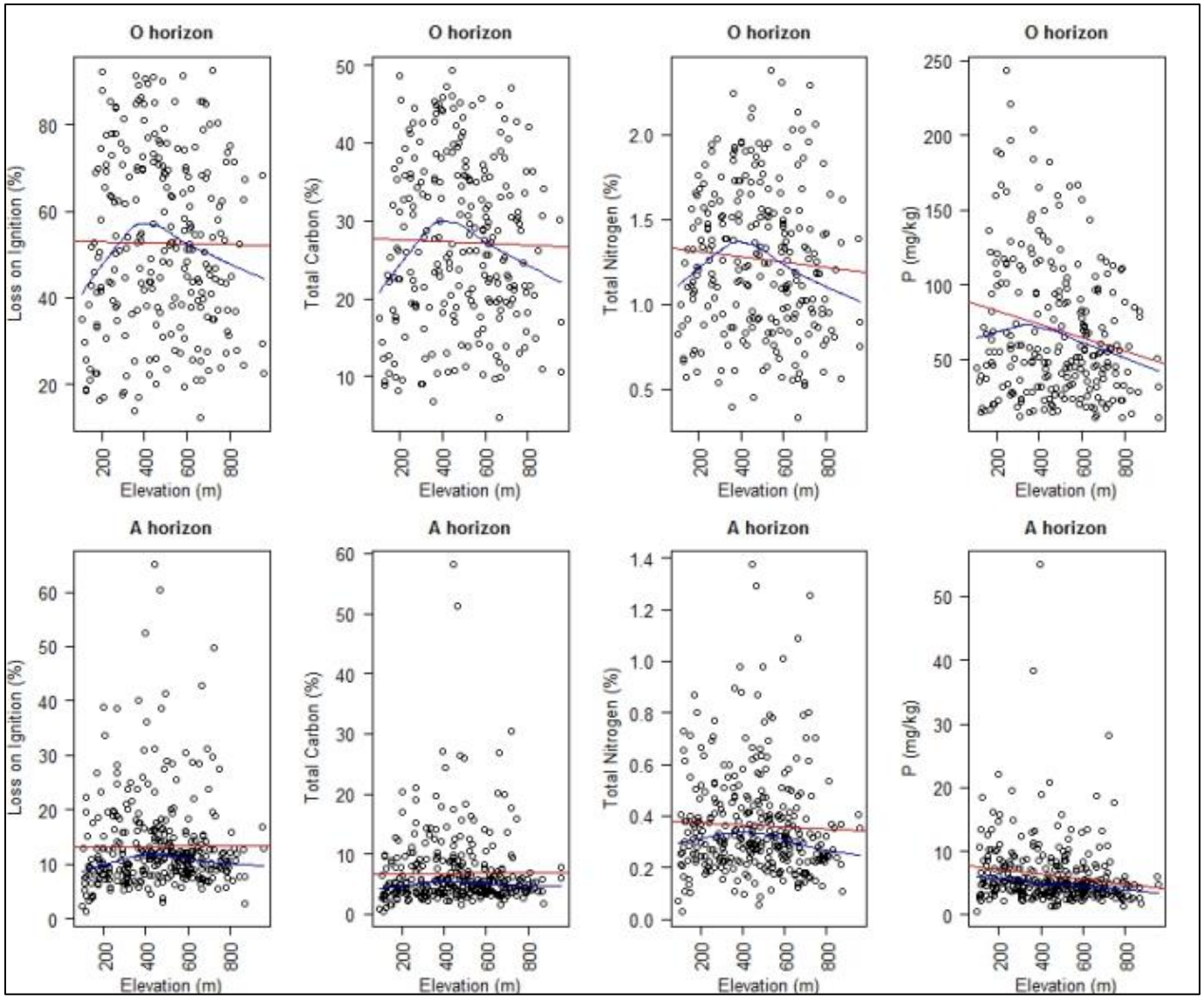

Figure D3. Carbon and nitrogen soil parameters plotted against elevation of monitoring plot. Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in blue.

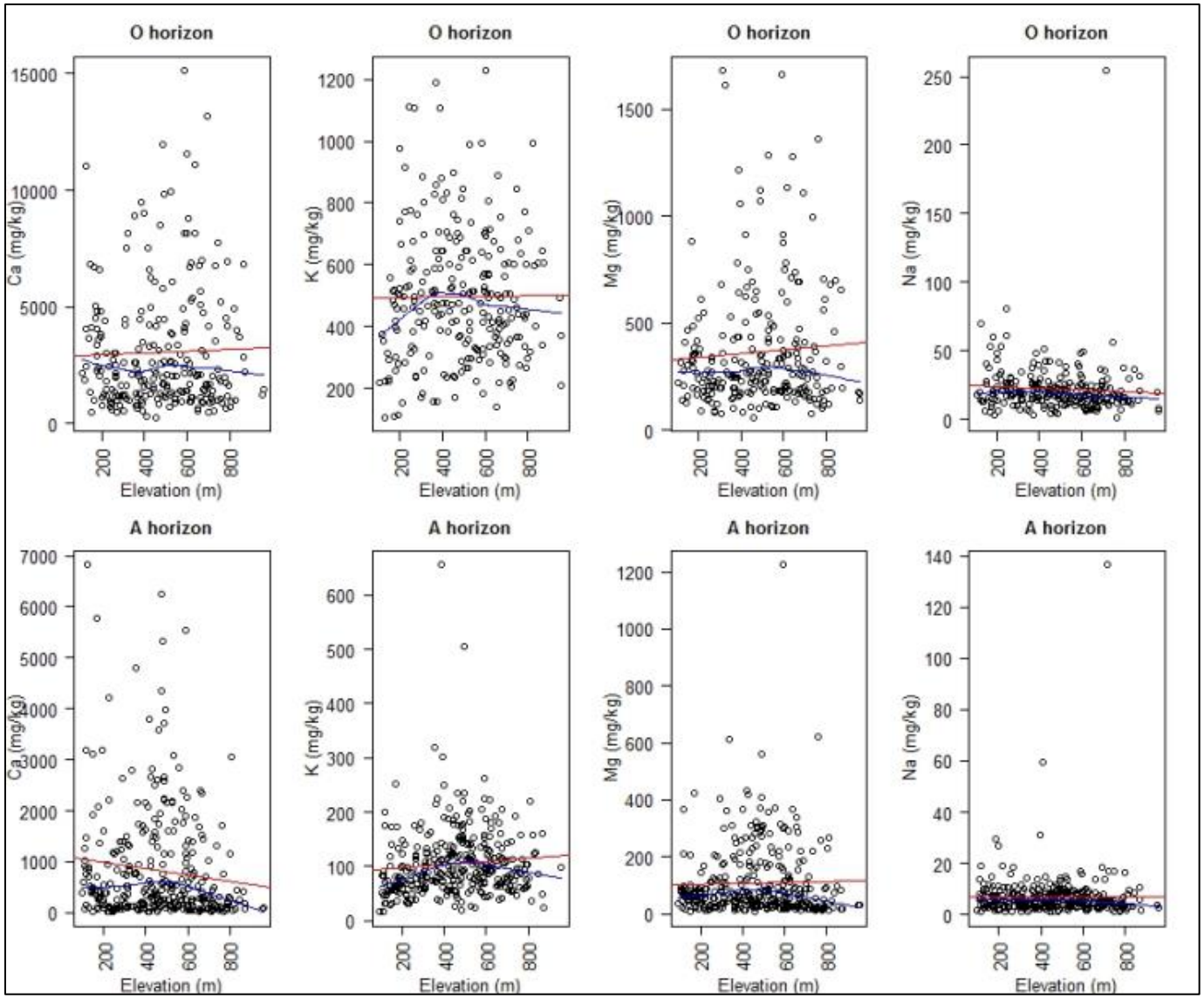

Figure D4. Base cations plotted against elevation of monitoring plot. Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in blue.

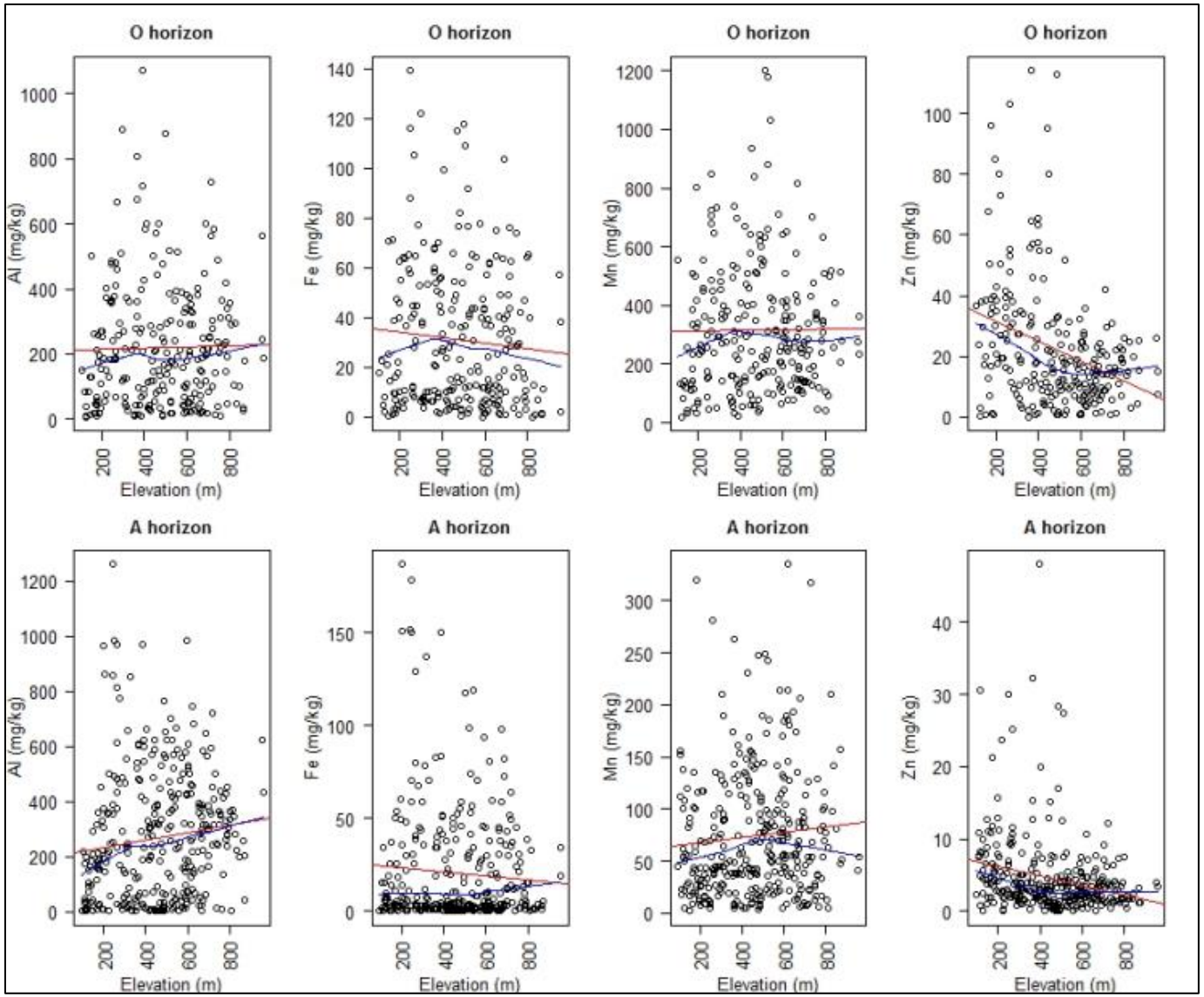

Figure D5. Acid cations plotted against elevation of monitoring plot. Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in blue.

Appendix E. Boxplots for soil variables by soil drainage class.

Using the NRCS Soil Surveys (USDA 2013 a, b, c, d, e, f, g, and h), each plot was attributed with a soil drainage class based on the plot's location within the survey. The soil drainage classes (Soil Survey Division Staff 1993) were then grouped into four categories:

A = Very poorly drained, poorly drained, and somewhat poorly drained soils

Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. The occurrence of internal free water commonly is shallow to moderately deep and transitory to permanent. Wetness markedly restricts or prevents the growth of mesophytic crops, unless artificial drainage is provided. The soils are commonly level or depressed and frequently ponded. The soils commonly have one or more of the following characteristics: low or very low saturated hydraulic conductivity, a high water table, additional water from seepage, or nearly continuous rainfall.

B = Moderately well drained soils

Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent. The soils are wet for only a short time within the rooting depth during the growing season, but long enough that most mesophytic crops are affected. They commonly have a moderately low or lower saturated hydraulic conductivity in a layer within the upper 1 m, periodically receive high rainfall, or both.

C = Well drained soils

Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified. Water is available to plants throughout most of the growing season in humid regions. Wetness does not inhibit growth of roots for significant periods during most growing seasons. The soils are mainly free of the deep to redoximorphic features that are related to wetness.

D = Some what excessively drained soils

Water is removed from the soil rapidly. Internal free water occurrence commonly is very rare or very deep. The soils are commonly coarse-textured and have high saturated hydraulic conductivity or are very shallow

Table E1. The number of plots per soil drainage category at which soils were collected.

	Soil Drainage Class				
Horizon	**A**	**B**	**C**	**D**	**Total**
O	10	39	161	35	245
A	18	59	225	32	334
Total	28	98	386	67	

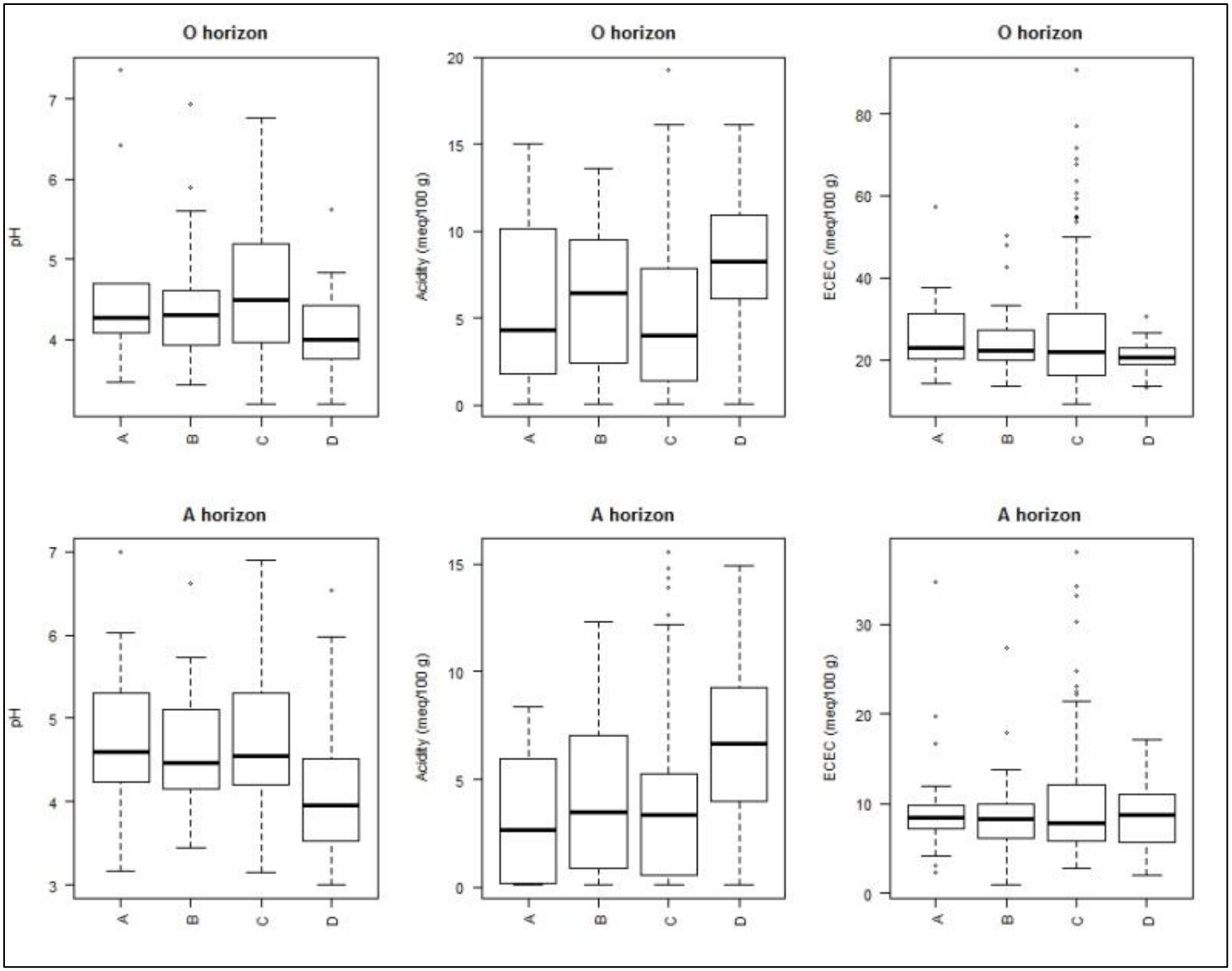

Figure E1. Soil parameters for each soil drainage category by horizon.

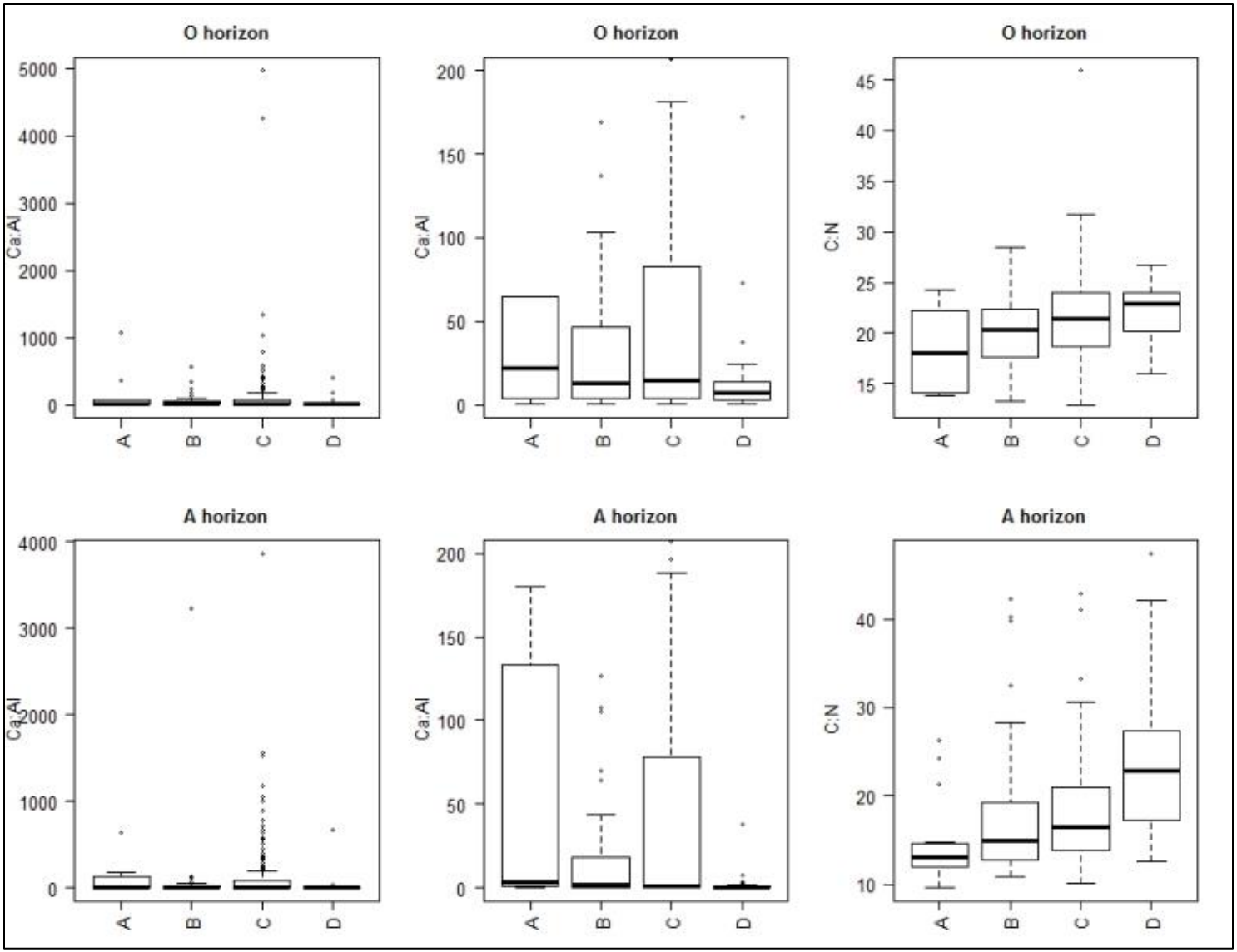

Figure E2. Ca:Al and C:N ratios for each soil drainage category by horizon. The second column of Ca:Al shows the lower range of ratio values for the parks.

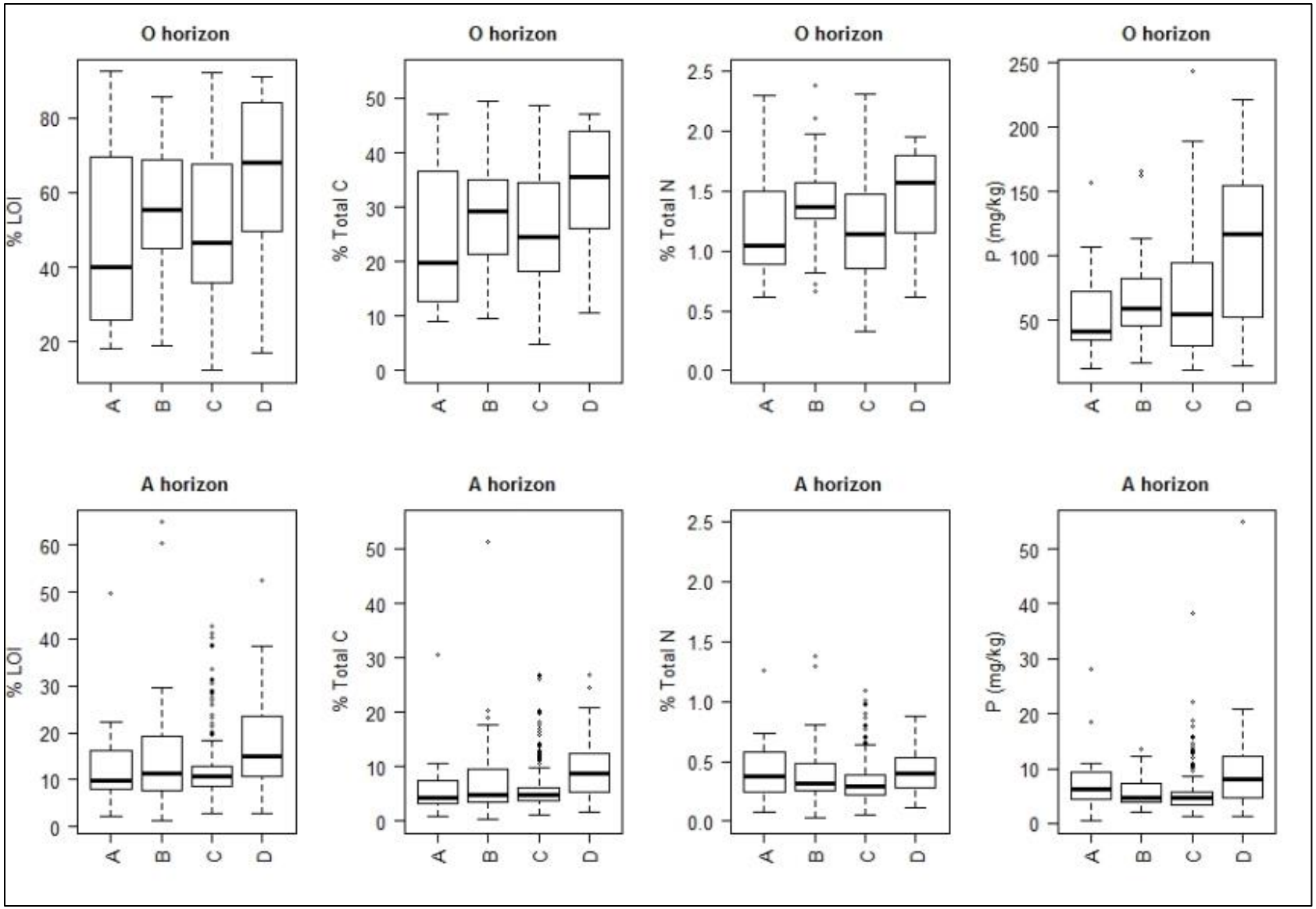

Figure E3. C and N parameters for each soil drainage category by horizon.

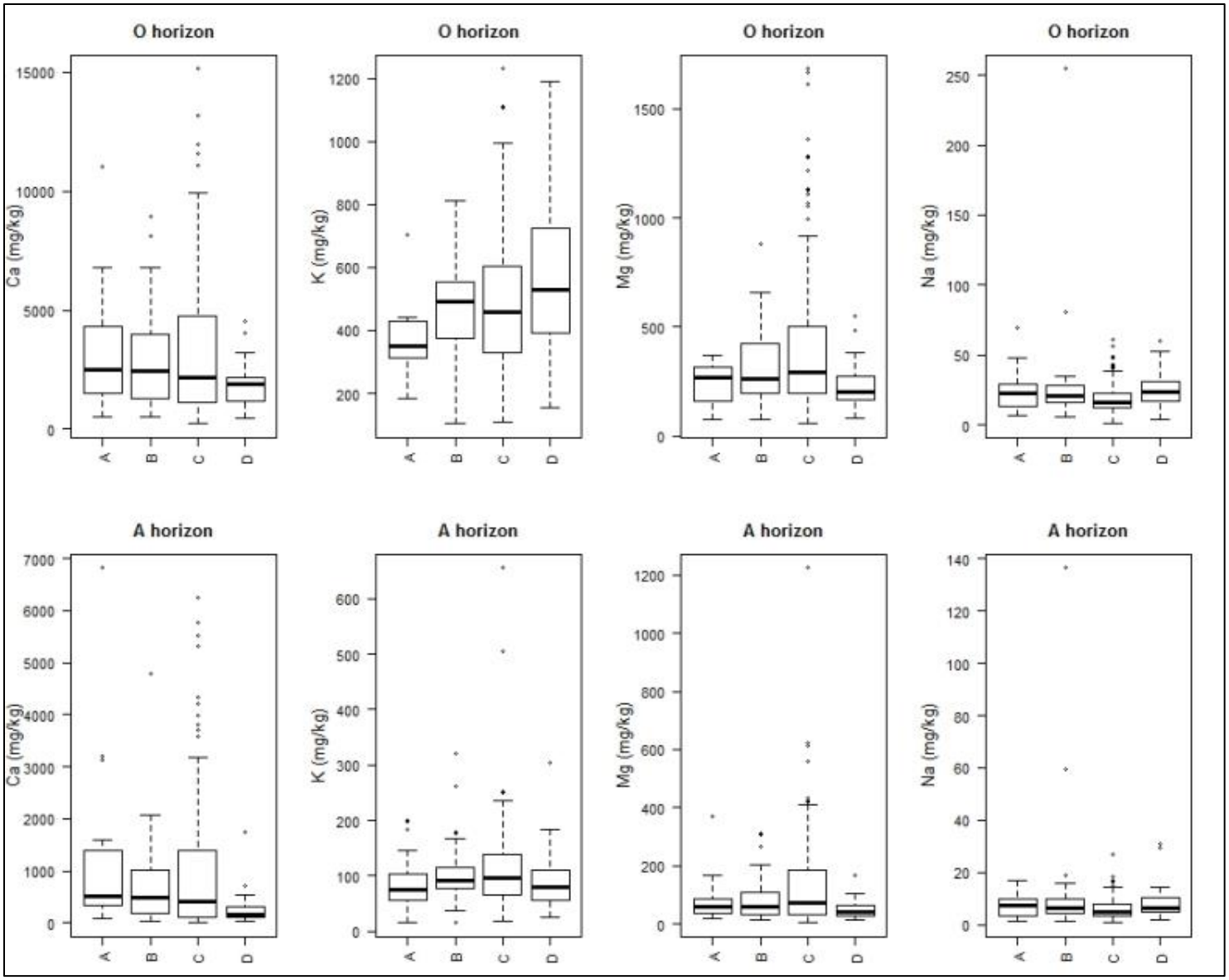

Figure E4. Base cations for each park unit by ho for each soil drainage category by horizon.

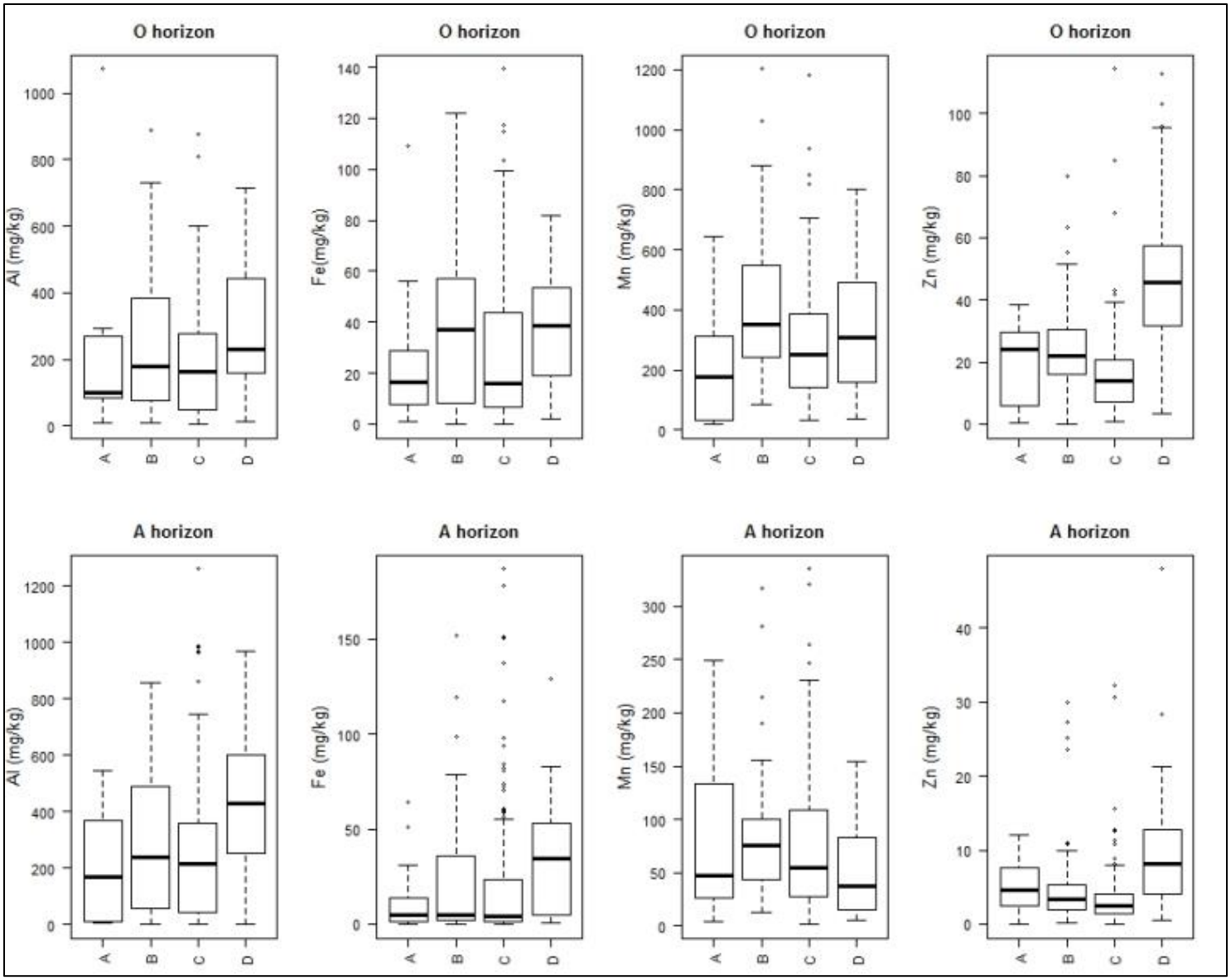

Figure E5. Acid cations for each soil drainage category by horizon.

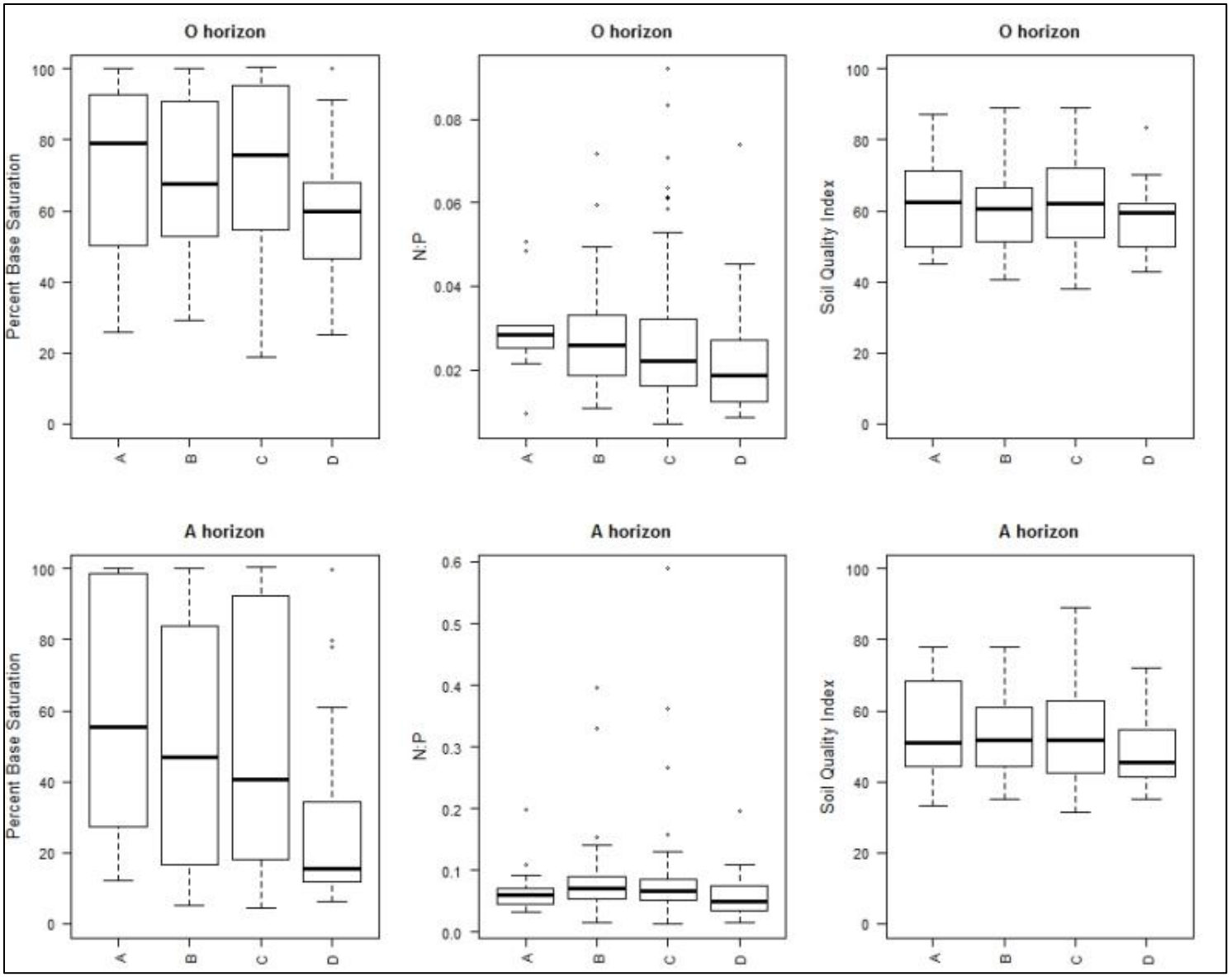

Figure E6. Percent base saturation, N:P and soil quality index for each soil drainage category by horizon.

Appendix F. Boxplots for soil variables by park.

Table F1. Park abbreviations and the state in which they occur.

Park abbreviations	Park name and state in which it occurs
ALPO	Allegheny Portage Railroad National Historical Park, PA
BLUE	Bluestone Scenic River, WV
DEWA	Delaware Water Gap National Recreational Area, PA / NJ border
FONE	Fort Necessity National Battlefield, PA
FRHI	Friendship Hill National Historic Site, PA
GARI	Gauley River National Recreation Area, WV
JOFL	Johnstown Flood National Memorial, PA
NERI	New River Gorge National River, WV

Table F2. The number of plots per park at which soils were collected.

Horizon	ALPO	BLUE	DEWA	FONE	FRHI	GARI	JOFL	NERI	Total
A	18	39	94	20	20	39	8	96	334
O	16	15	80	15	6	30	7	76	245
Total	34	54	174	35	26	69	15	172	579

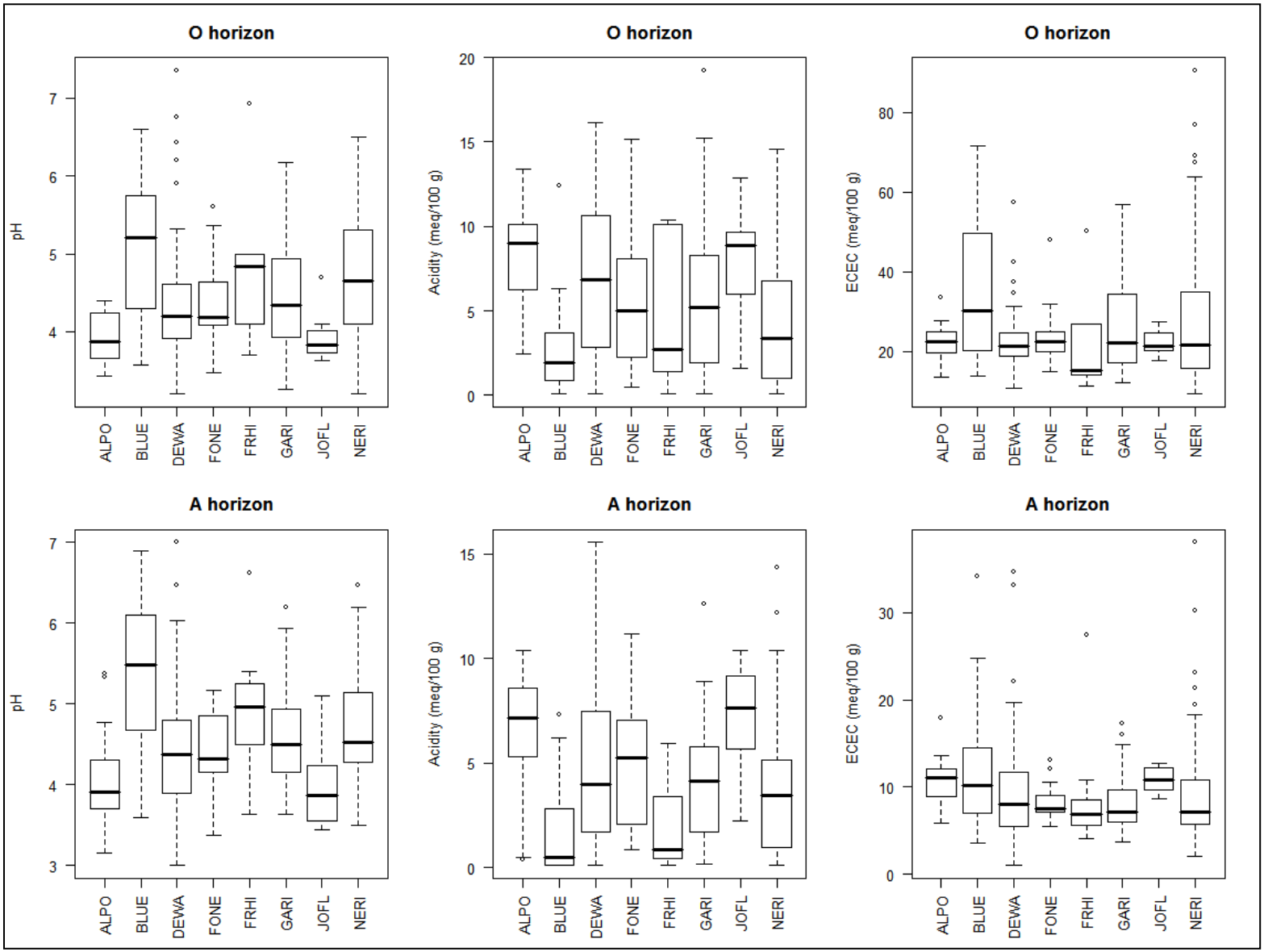

Figure F1. Soil parameters for each park by horizon.

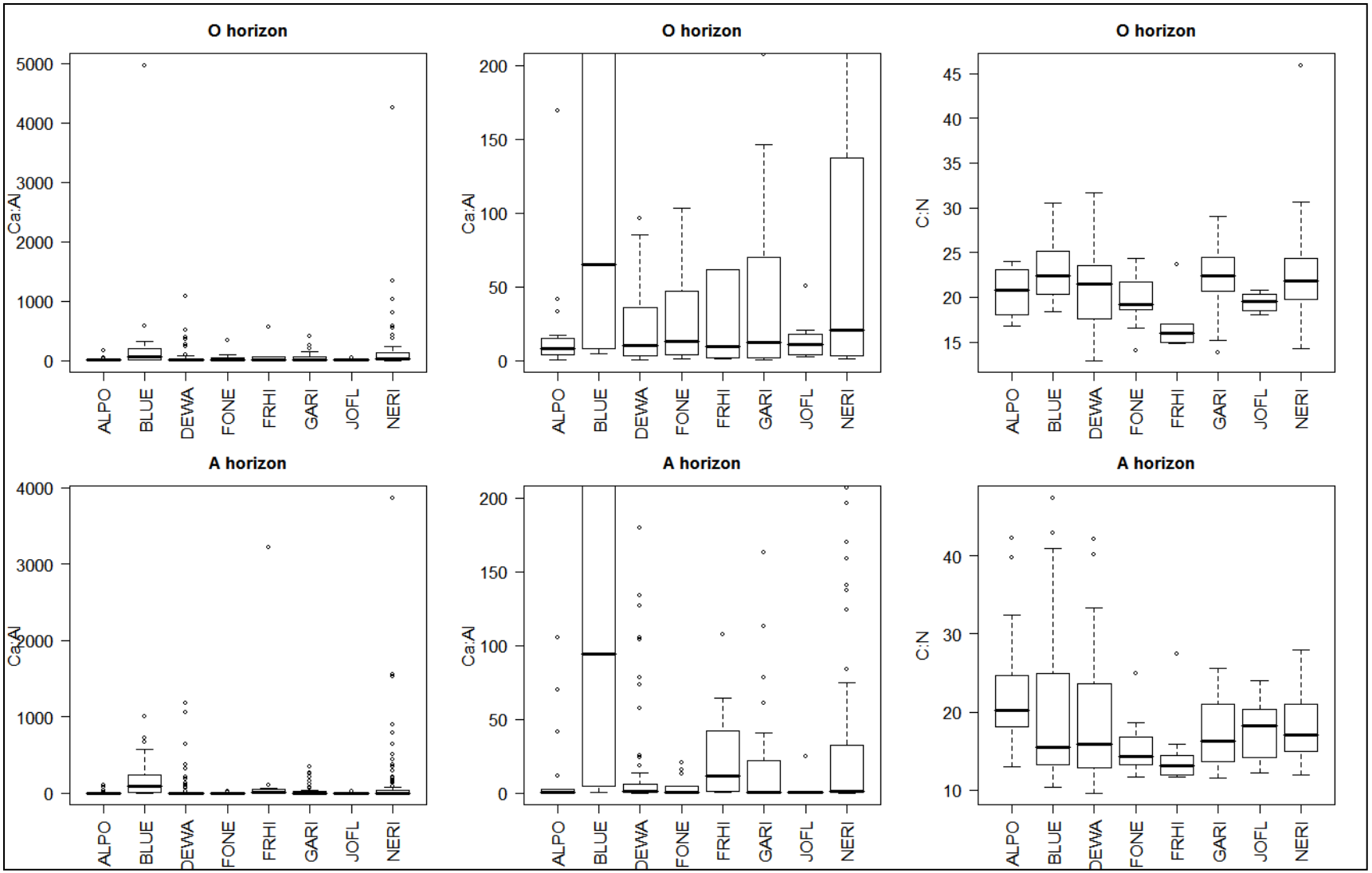

Figure F2. Ca:Al and C:N ratios for each park unit by horizon. The second column of Ca:Al shows the lower range of ratio values for the parks.

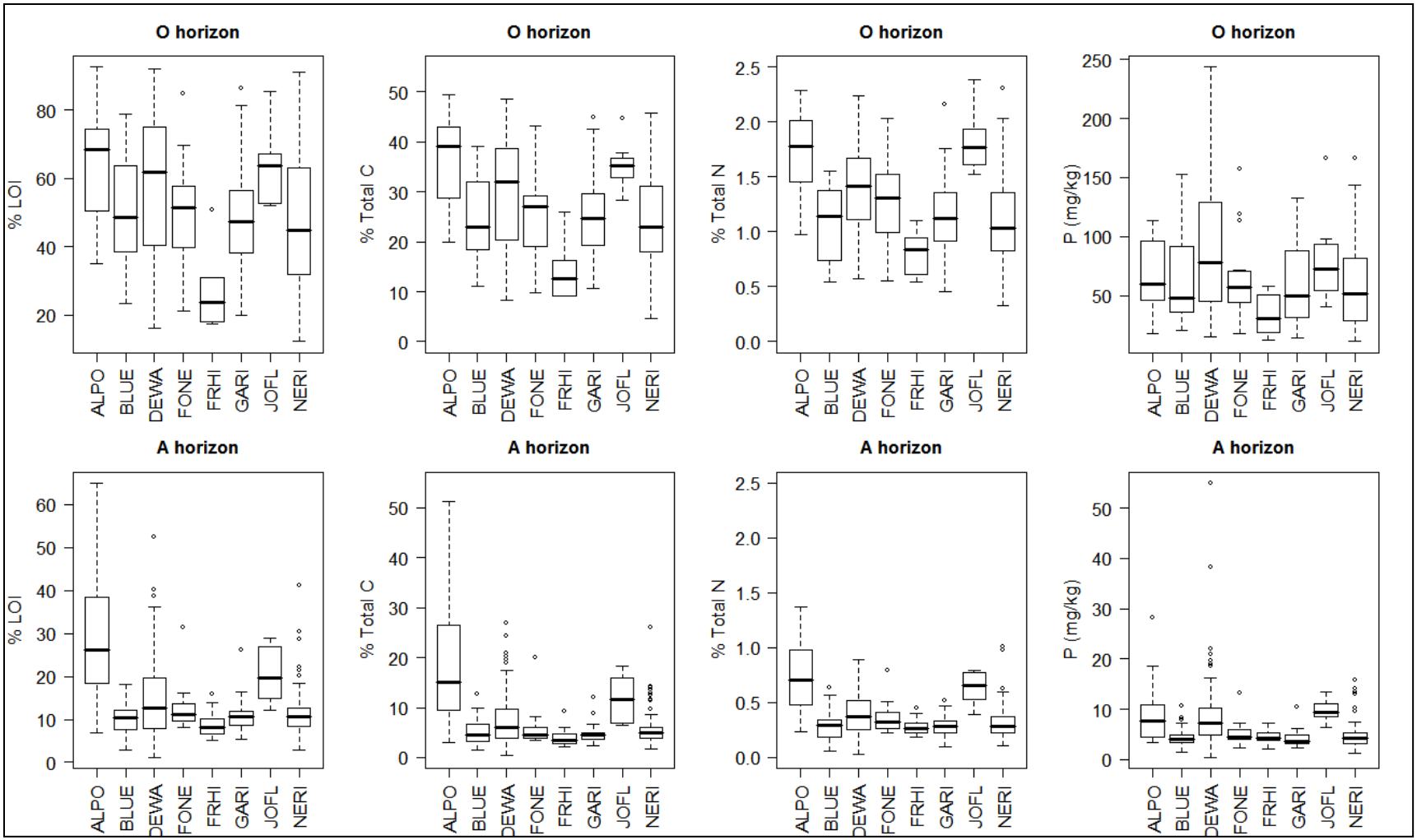

Figure F3. C and N parameters for each park unit by horizon.

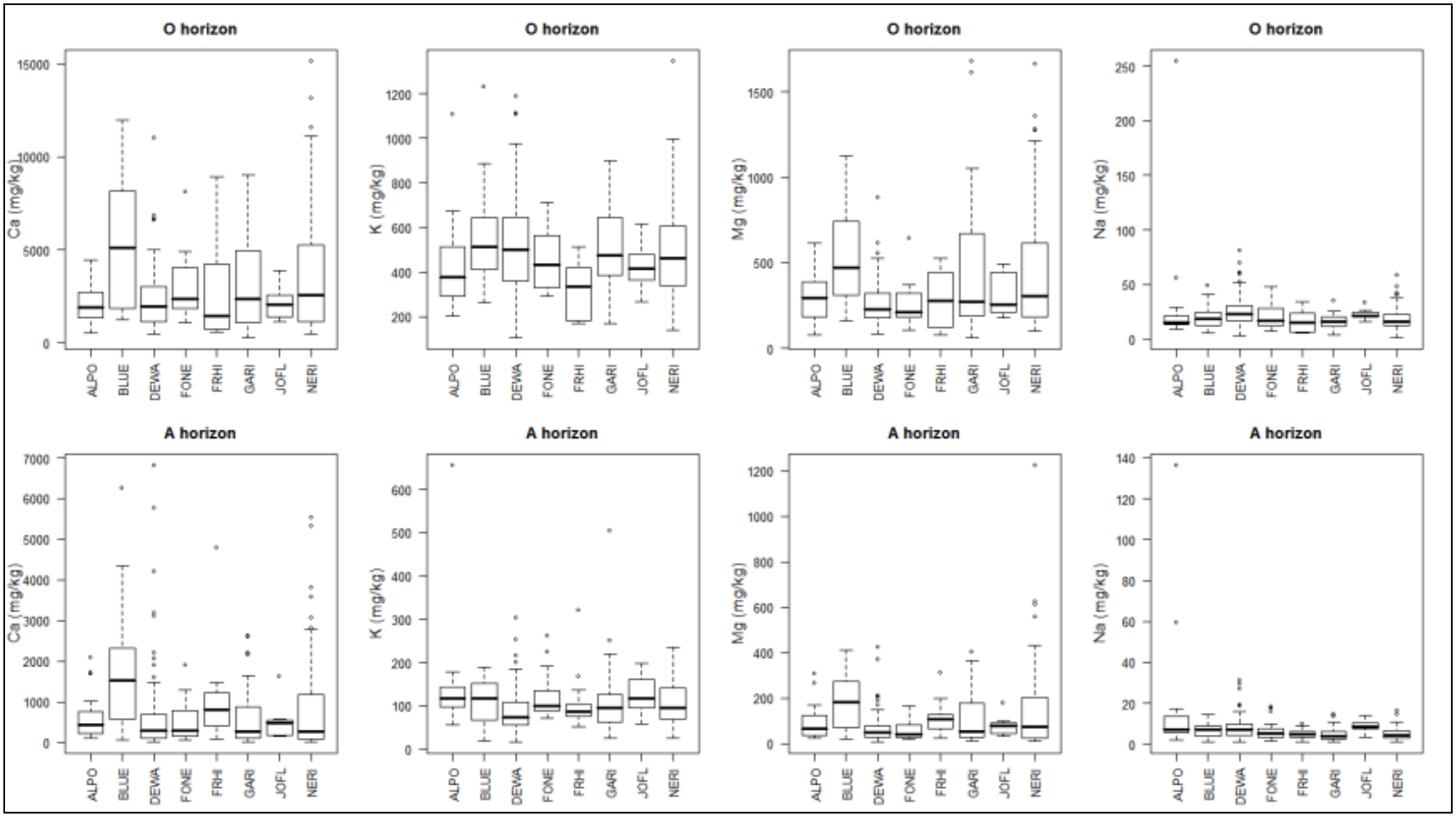

Figure F4. Base cations for each park unit by horizon.

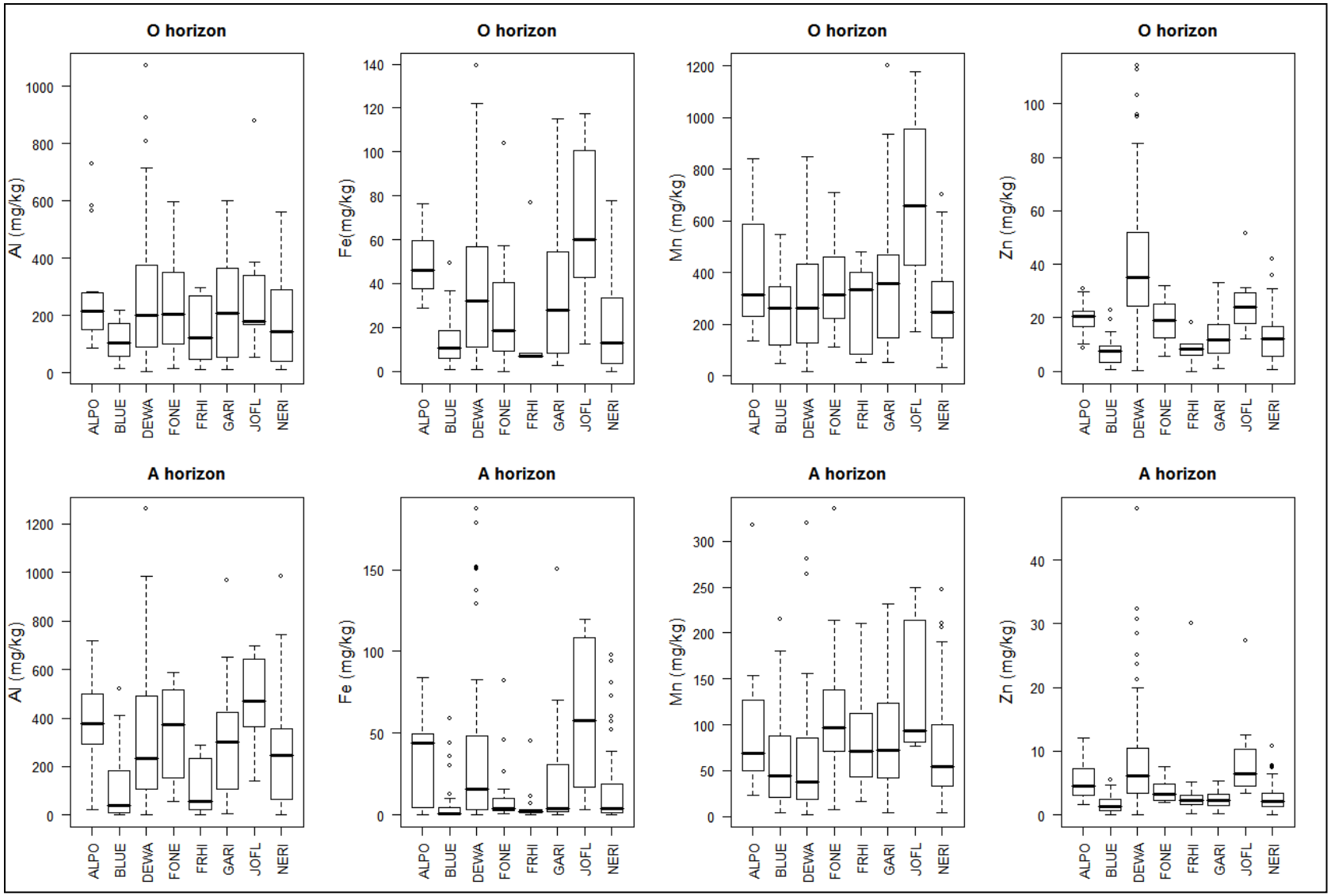

Figure F5. Acid cations for each park unit by horizon.

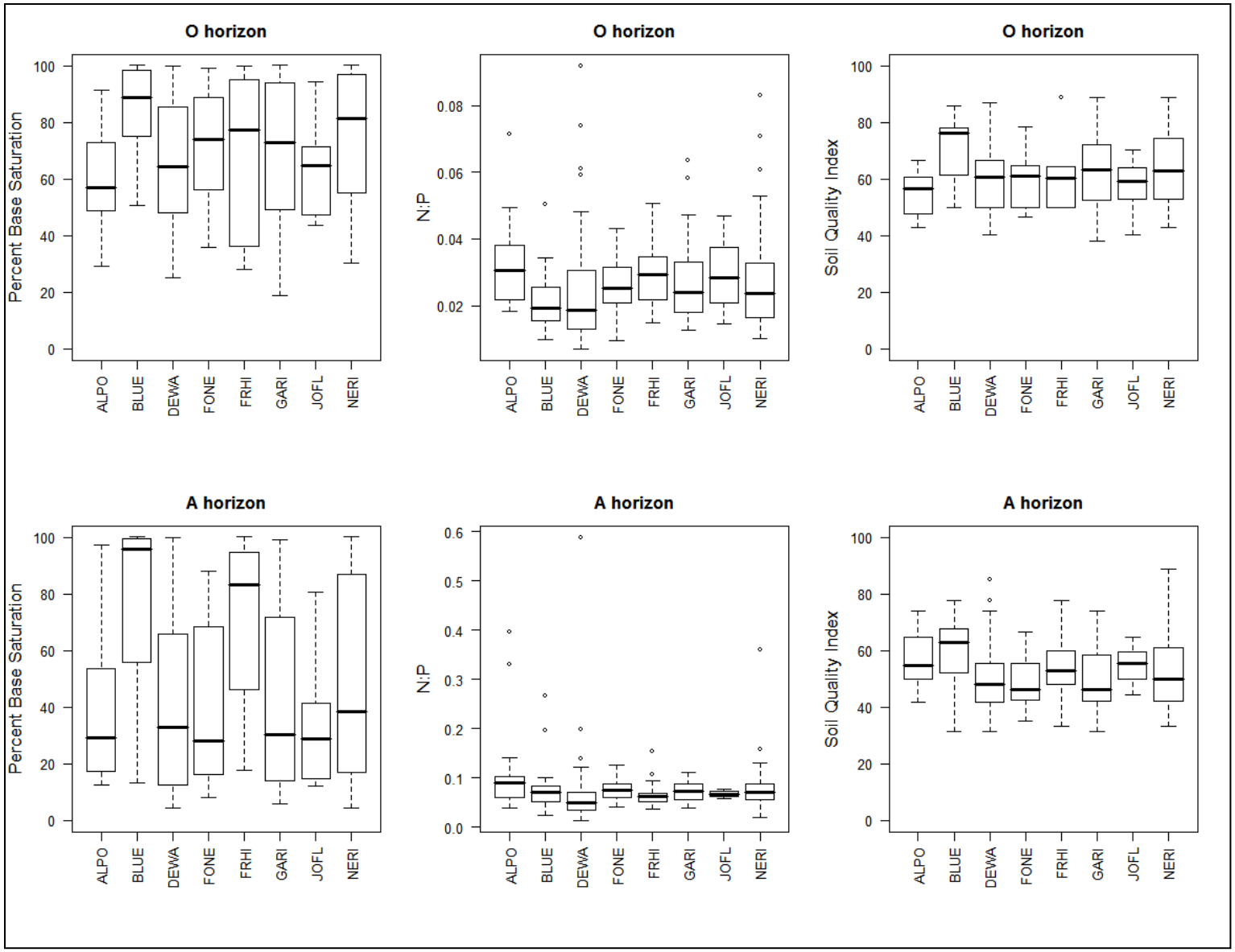

Figure F6. Percent base saturation, N:P and soil quality index for each park by horizon.

Appendix G. Analysis and interpretation of Ca:Al ratio.

One of the most frequently cited indicators of forest soil health is the Ca:Al ratio thresholds published by Cronan and Grigal (1995) who proposed that when the Ca:Al ratio in soil solution falls below 1.0, there is a 50% risk of adverse impacts on tree growth. Risk increases to 75% risk when the soil solution Ca:Al ratio is as low as 0.5, and nearly a 100% risk when the soil solution Ca:Al molar ratio is as low as 0.2 (Cronan and Grigal 1995). However, measuring soil solution chemistry in the field requires lysimeters and is not practical for large scale long-term monitoring programs such as ERMN. Furthermore, the thresholds proposed by Cronan and Grigal (1995) were established based on trees seedlings grown hydroponically, in a system that was free from organic matter. Since the complexation of Al with organic matter in soil (as opposed to soil water) can greatly reduce the toxicity of Al, the Cronan and Grigal (1995) thresholds are not applicable for values of Ca and Al extracted directly from soil. The ammonium chloride (NH_4Cl) extractant that is used to analyze ERMN soil samples removes more Al from the soil than would typically be available to plant roots in soil solution in situ. Therefore, comparison between the Cronan and Grigal (1995) thresholds and the ERMN Ca:Al values obtained using the NH_4Cl extractant are not appropriate.

As an alternative, a 0.01 M strontium chloride ($SrCl_{2)}$ can be used to extract Ca and Al from soil samples. The amount of Al extracted from soil by $SrCl_2$ in the laboratory is closely correlated with the amount of Al in fine root tissue and with root growth (Joslin and Wolfe 1988). The $SrCl_2$ extractant approximates the amount of Ca and Al available to plants in soil solution, allowing for comparison to the Cronan and Grigal (1995) (Lyon and Sharpe 1999). This extractant should be used only on mineral soils, not on O horizon soils, to minimize the effects of organic matter on Al availability. Based on numerous studies, condition thresholds for the Ca:Al ratio using the $SrCl_2$ extractant could be proposed as shown in Table G1.

Table G1. Potential condition thresholds for the soil Ca:Al ratio using $SrCl_2$ extractant.

Ca:Al Ratio from 0.01M $SrCl_2$	Condition	Citations
< 1.00	Poor	Sverdrup et al. (1994), Sverdrup et al. (1996), Demchik et al. (1999), and Demchik and Sharpe (1999)
1.01 – 3.00	Significant Concern	Sverdrup et al. (1994), Sverdrup et al. (1996), Demchik et al. (1999)
> 3.00	Good	Demchik et al. (1999)

We selected a subset of 232 soil samples from the ERMN parks to be analyzed using 0.01 M $SrCl_2$. Samples were selected using the following criteria: a) mineral soil, b) sufficient archived soil that removing soil for this analysis would not depleted the archived soil sample such that future analyses could not be conducted, c) one sample per plot was randomly selected from the available samples. These samples were analyzed at Pennsylvania State University's Agricultural Analytical Services Laboratory.

Using the results of the 0.01M SrCl2 extraction and the condition benchmarks listed above, Figure 1 shows the percentage of samples in each condition category by park.

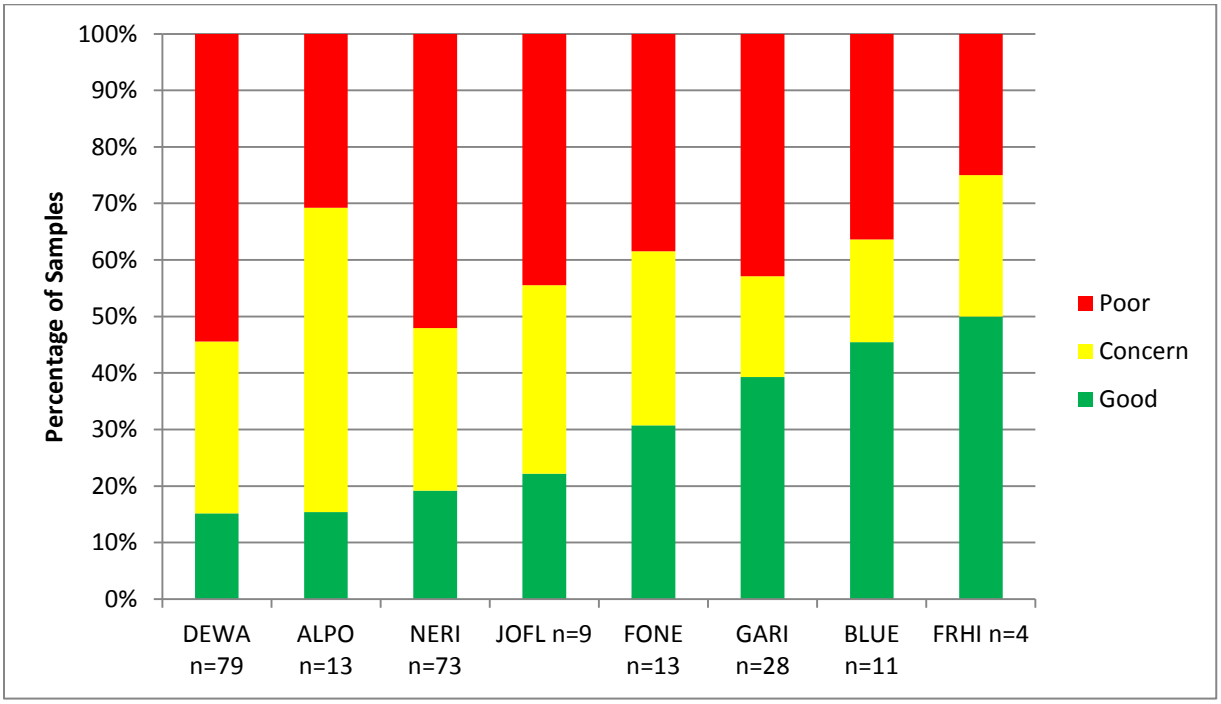

Figure G1. Percentage of plots in soil condition categories based on Ca:Al ratios extracted with 0.01 M $SrCl_2$.

These results concur with findings presented elsewhere in this report. BLUE and FRHI have more samples in “Good” condition, while DEWA, NERI, ALPO and JOFL tend to have more samples in “Poor” or “Significant Concern” condition. These differences are caused by the calcareous-influenced bedrock underneath BLUE and FRHI that leads to richer soils with more buffering capacity against acidic deposition. Also, ALPO and JOFL occur at higher elevations in areas of high deposition of sulfur and nitrogen which may lead to reduced Ca and elevated Al. Soils on the ridgetops of DEWA and NERI that occur at higher elevations over acidic bedrock tend to be most Ca depleted and have higher amounts of Al.

ERMN soil samples are analyzed with ammonium chloride (NH_4Cl) as the extractant, as is standard for most forest soil analysis methods for available nutrients from the eastern United States. In order to utilize the condition thresholds presented above, additional funding would be required to analyze soil using the SrCl2 extractant as well. However, a strong correlation between Ca:Al ratio extracted with $SrCl_2$ and Ca:Al ratio extracted with NH_4Cl would facilitate the interpretation of risk to the forest based on the NH_4Cl extracted Ca:Al ratio. To this end, two datasets were examined: the subset of 232 ERMN soil samples, and data provided by the US Forest Service from 646 soil samples from the Monongahela National Forest in West Virginia. Linear regressions were run and data were graphed using xy plots for both data sets in the R statistical software (R Development Core Team 2011, Figures 2 and 3). Regression equations, r^2 values, and potential threshold values calculated using the regression equations are shown in Table G2. However, the r^2 values of 0.69 for the ERMN data and 0.47 for the USFS data indicate that a useful correlation is not available. Aluminum is present in numerous chemical forms in soil, and as a result is one of the more difficult elements to precisely extract in the laboratory.

Table G2. Regression equations, r^2 values, and potential threshold values for Ca:Al ratios as extracted by NH_4Cl and $SrCl_2$.

Threshold Values for Ca:Al Ratio ($SrCl_2$ extractant)	**Calculated Values for Ca:Al Ratio (NH_4Cl extractant)**	
	USFS Data	**ERMN data**
	y = 0.1023x + 0.0334 r^2 = 0.4694	**y = 0.119304x + 0.057722 r^2=0.6901**
0.2	0.0539	0.0816
0.5	0.0845	0.1174
1.0	0.1357	0.1770
3.0	0.3403	0.4156
4.0	0.4426	0.5349

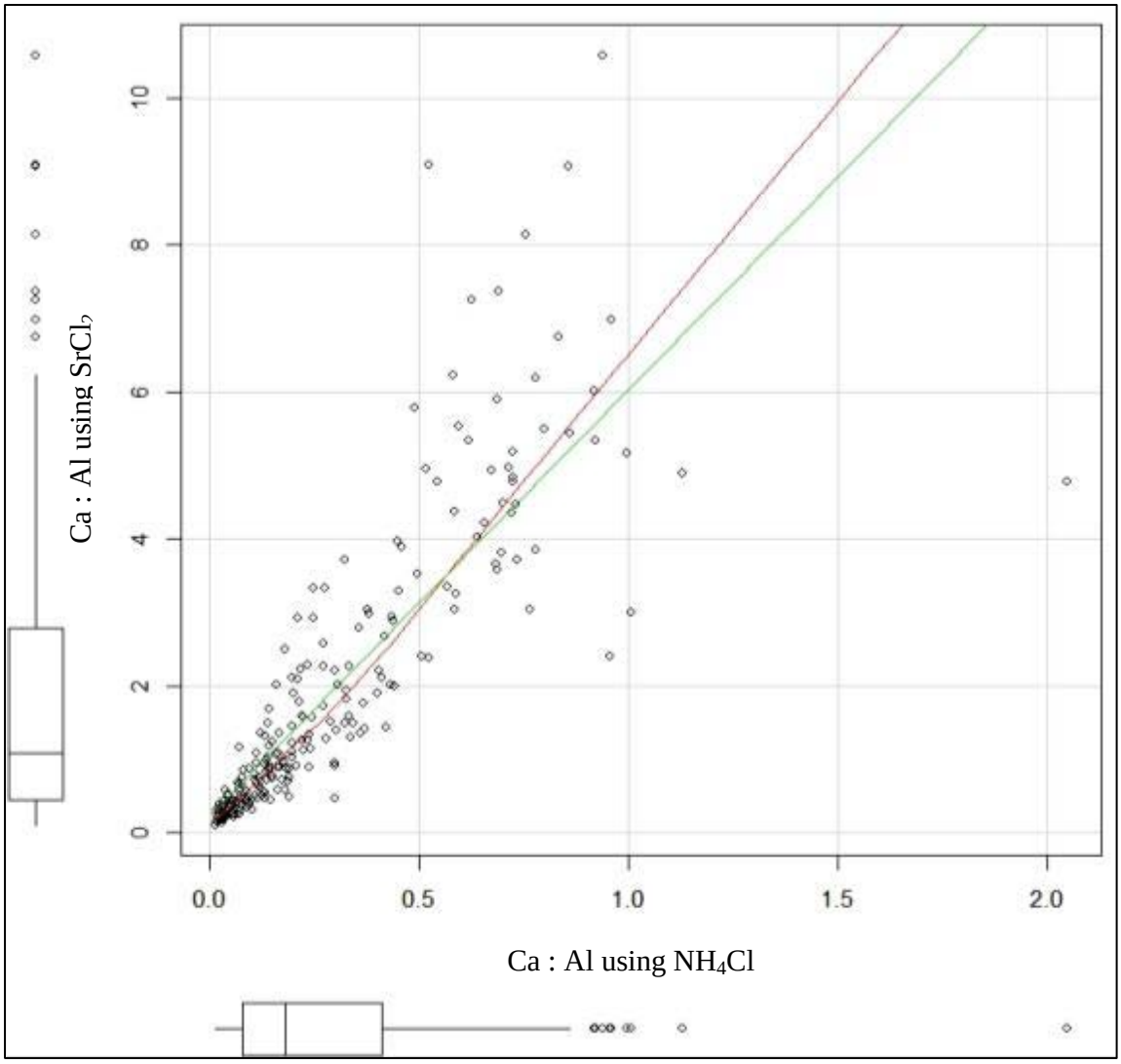

Figure G2. Correlation between Ca:Al ratio extracted with NH_4Cl and $SrCl_2$. Data from the national parks in the Eastern Rivers and Mountains Network from New Jersey to West Virginia (n=232). Red lines show the linear regressions. LOWESS (locally weighted scatterplot smoothing) curves are shown in green.

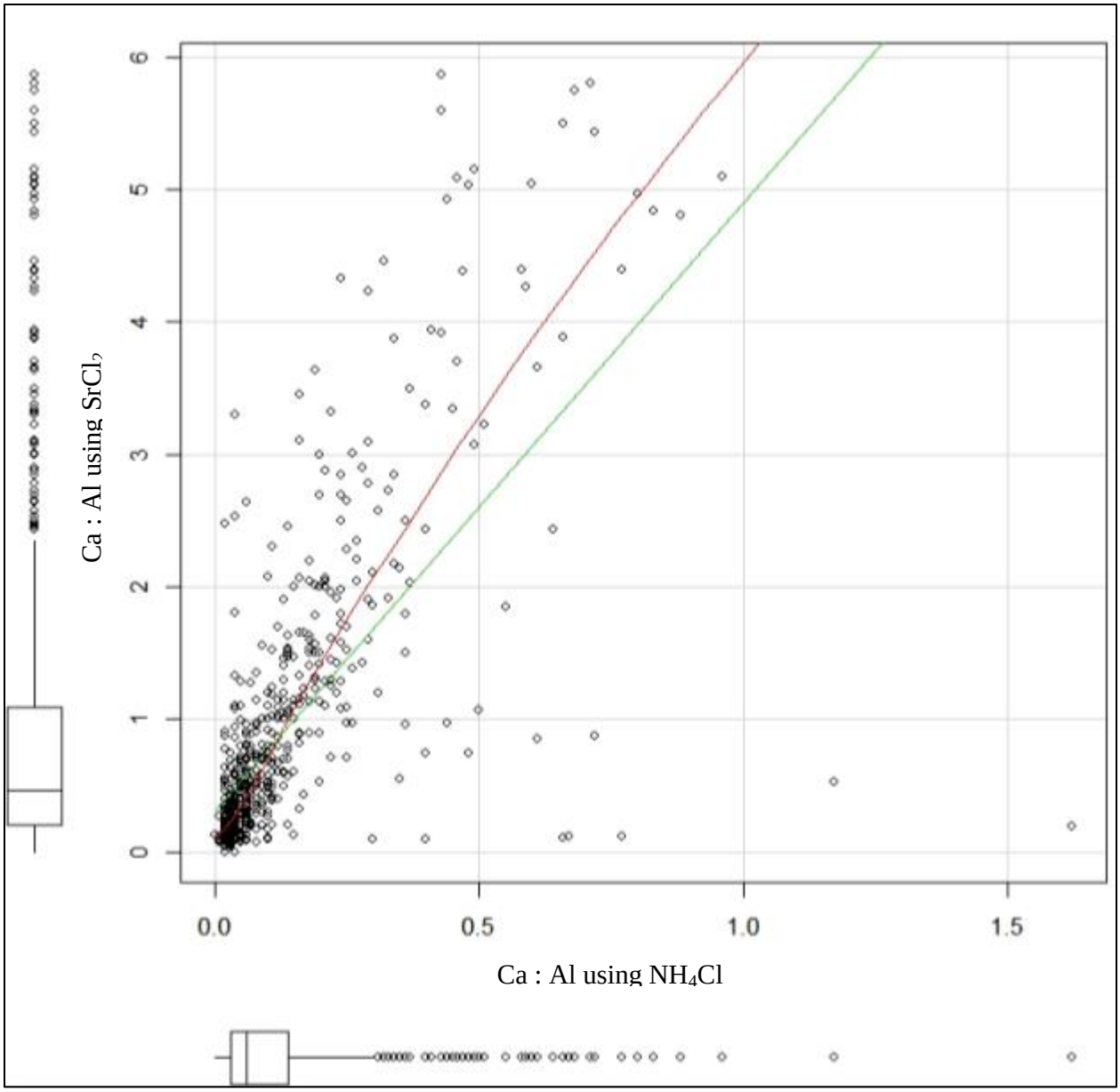

Figure G3. Correlation between Ca:Al ratio extracted with NH_4Cl and $SrCl_2$. Data from the Monongahela National Forest in West Virginia (n=646). Red line shows the linear regression. LOWESS (locally weighted scatterplot smoothing) curves are shown in green.

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