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Natural Resource Stewardship and Science

Physical and Chemical Properties of Forest Soils in the National Capital Region Network

Natural Resource Report NPS/NCRN/NRR—2020/2151

ON THIS PAGE
Soil profiles highlighting the diversity of horizons, color and texture found throughout the National Capital Region Network.
Photograph by: Daniel Colopietro

ON THE COVER
The first author assessing soil profile characteristics in Catoctin Mountain Park.
Photograph by: Thomas Paradis

Physical and Chemical Properties of Forest Soils in the National Capital Region Network

Natural Resource Report NPS/NCRN/NRR—2020/2151

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Executive Summary

Soils are the foundation of terrestrial ecosystems and affect all parts of the environment: water, atmosphere, animals, vegetation, and climate. To better understand soil function and the influence of soil morphology and nutrients on vegetation in urban and semi-urban forested ecosystems of the Mid-Atlantic, the National Capital Region Network (NCRN) collected a suite of soil physical and chemical data in the 426 permanent vegetation monitoring plots in 11 park units between 2007 and 2017.

This report details the data collection methods and summarizes the soil physical and chemical data. The objectives of the report are to:

1. Describe the physical and chemical characteristics of soils in the NCRN.
2. Provide baseline soils data to aid park managers and future long-term soil monitoring in the NCRN.
3. Identify statistically significant differences among soil variables found at NCRN parks and discuss the probable causes of these differences.
4. Highlight individual plots with outlier characteristics that might negatively affect ecosystem function or require further investigation.
5. Discuss future opportunities for soil monitoring and scientific studies in the NCRN.

At each of the 426 plots, a full soil profile description was made to a depth of 100 cm (when possible) consisting of: master and subordinate horizons, clay percentage, coarse fragments, colors, redoximorphic features, consistence, and soil structure. Measured soil physical variables were: aggregate stability, bulk density (D_b), unsaturated and saturated infiltration, penetration resistance, and volumetric water content (θ_v). Soil chemical analyses were conducted on master horizons to a depth of 100 cm and on composite samples from the surface of the plot (O and A horizons) to account for intra-plot spatial variability. Analyzed soil chemical variables included: total carbon (C), total nitrogen (N), pH, cation exchange capacity (CEC), and extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), molybdenum (Mo), cadmium (Cd), Chromium (Cr), and lead (Pb). The Methods section details data collection, inventory and analyses.

The Results section is divided into six subsections. ANOVAs were used to determine significant differences between variables by park, and the first subsection highlights the significant differences between physical characteristics while the second subsection focuses on chemical variables. The third subsection summarizes the results of a regression analysis that was conducted to determine the relationship between three master soil variables—C, pH, and clay percent—and all other chemical variables. The fourth subsection details significant chemical variable differences horizon by horizon among the parks. An overview of the NCRN's soil series, relative soil depths, drainage and other horizon characteristics is presented in the fifth subsection. To assist NPS managers, the sixth and final subsection summarizes and inventories the soils in each of the region's 11 parks including

individual plots with unique soils features and other outstanding soil characteristics within the context of the NCRN.

Overall, the Results show a high diversity of soil types across the NCRN, including 85 soil series from 4 soil orders. Ultisols dominate the region and are found in approximately 60% of plots according to Web Soil Survey. Alfisols comprise 22% of the plots—mostly in the Ridge & Valley physiographic region. Inceptisols are found in many of the mountain plots (17% of the total), and six plots located near rivers or streams have Mollisols.

Physical characteristics also vary greatly. Rocky soils in Catoctin were typically very shallow, whereas soils of the National Capital Parks-East on the Coastal Plain were frequently quite deep. The subsoil (B horizon) of Harpers Ferry contained half the clay of subsoil in Antietam (16% compared to 32%). The physical characteristics affected soil physical measurements. For instance, mean infiltration rates in Antietam were one third of the mean rate in Catoctin, and the lowest D_b values of the region were also observed at Catoctin. Manassas National Battlefield Park, with high amounts of clay, could also hold the greatest amount of water in the region.

Chemical characteristics likewise differ significantly by park, with Prince William Forest Park having the lowest nutrient levels in the NCRN and the parks in the Blue Ridge and Ridge & Valley physiographic regions—Antietam, Catoctin, and Harpers Ferry—having the highest. Nutrient concentrations were far greater in the surface horizons (O and A) and decreased with depth. Very few soil contaminants were found in the NCRN, and overall the soils of the region are fertile.

The Discussion section highlights the importance of this report both within the context of the I&M program and also within the Mid-Atlantic region, and furthermore it highlights the report's potential to act as a template for future NPS soil inventory efforts. It then presents important patterns and ecological insights gleaned from the data. Finally, it outlines four important areas for future research that can be built off of the data in this report.

This report documents the first comprehensive assessment of soil chemical and physical characteristics in the NCRN. It provides valuable baseline data for future monitoring and advances our understanding of Mid-Atlantic forest ecology. Moreover, the soils data can be used in conjunction with vegetation data to guide forest management strategies and assess ecosystem health and services. Above all, this soils report furthers a key tenet of the NPS mission, "To guide park management using science."

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List of Park Acronyms

ANTI: Antietam National Battlefield

CATO: Catoctin Mountain Park

CHOH: Chesapeake and Ohio National Historical Park

GWMP: George Washington Memorial Parkway

HAFE: Harpers Ferry National Historical Park

MANA: Manassas National Battlefield Park

MONO: Monocacy National Battlefield Park

NACE: National Capital Parks-East

PRWI: Prince William Forest Park

ROCR: Rock Creek Park

WOTR: Wolf Trap National Park for the Performing Arts

Introduction

Overview of the NCRN

The National Parks Omnibus Management Act of 1998 directed the National Park Service (NPS) to "undertake a program of inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources" (Fancy et al. 2009). With the enactment of that legislation, the Inventory and Monitoring (I&M) Program was established to organize the nation's approximately 270 parks into 32 I&M networks based on geography and common natural resource characteristics.

Among the 32 I&M networks, the National Capital Region Network (NCRN) is the smallest by area. It consists of 11 park units situated predominantly in the Eastern Deciduous Forest ecosystem and spans 4 physiographic regions: Coastal Plain, Piedmont, Blue Ridge, and Valley & Ridge from east to west respectively (Figure 1). The underlying geology and topography are diverse. Parks situated on the Coastal Plain—NACE and a portion of PRWI—lie mostly at or near sea level and were primarily formed from sediments deposited by ancient seas and rivers that covered the area. Moving west, the Piedmont Plateau is sandwiched between the Coastal Plain and Blue Ridge and consists of metamorphic, igneous and sedimentary rocks punctuated by a fall line on its eastern edge. The Blue Ridge, which forms the easternmost edge of the Appalachian Mountains, is one of the oldest mountain chains in the world. The geology of this region is predominantly ancient igneous and metamorphic rocks. At the western flank of the NCRN, the Ridge and Valley system encompasses the Great Appalachian Valley (Hagerstown and Shenandoah being local variants) and other smaller valleys formed from carbonate rocks that were eroded down to form low points between more resistant sedimentary rocks of the ridges.

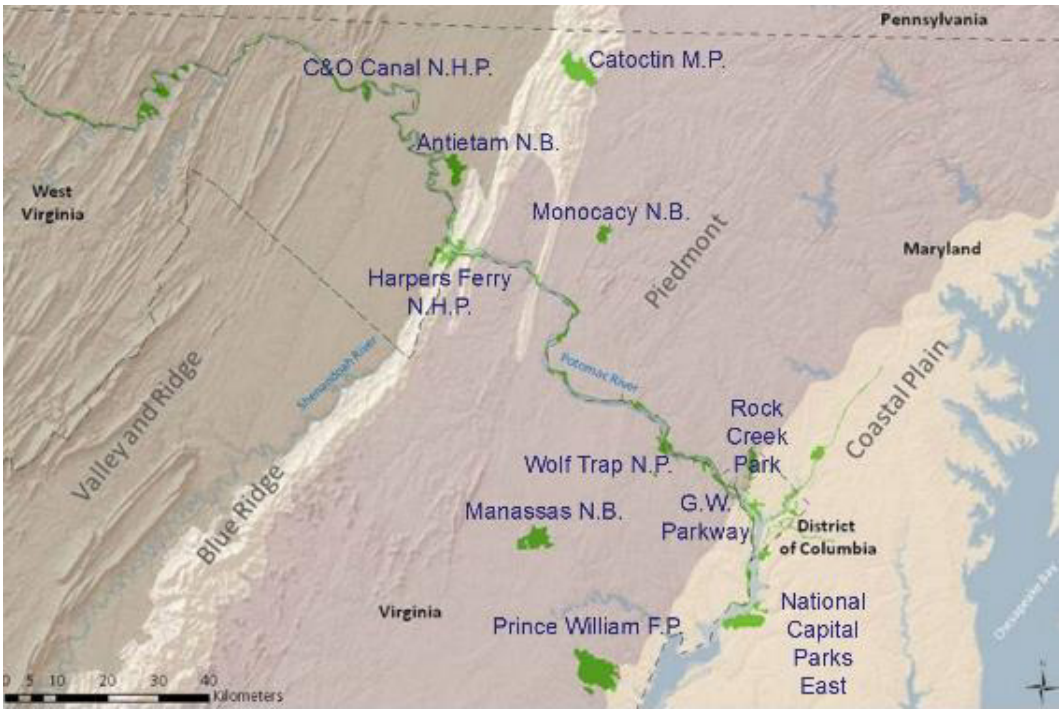

Figure 1. Location of National Capital Region parks (highlighted in green) and physiographic regions within the NCRN. (Source: NPS NCRN website)

Annual precipitation in the region is approximately 1000 mm spread relatively evenly throughout the year, though the months of May through October generally experience greater precipitation. Monthly average air temperatures range from 0 to 23ºC (January and July respectively).

Forests cover nearly three quarters of the area of the NCRN parks (Schmit et al 2012). Long-term forest monitoring plots in the NCRN have documented 81 tree species in the region, a large proportion of which are deciduous hardwoods such as tulip tree (*Liriodendron tulipifera*), red maple (*Acer rubrum*), American beech (*Fagus grandifolia*), and white oak (*Quercus alba*) (Schmit et al. 2012). Virginia pine (*Pinus virginiana*) is the most common coniferous tree in the region. Tree density (the number of woody plants ≥10 cm diameter at breast height) averages 400 ha^{-1} across the region, with park averages ranging from 200 to 500 trees ha^{-1}.

The small size of the NCRN belies its large environmental significance. The importance of the region's parks arises from their location, ecology, and ecosystem services. At the center of the 6th largest metropolitan area in the country—DC-VA-MD-WV—with a population of over 6.2 million (U.S. Census Bureau 2018), the NCRN provides important recreational opportunities to an urban population. Four of the NCRN's 11 parks (GWMP, CHOH, ROCR, NACE) recorded over 1 million recreational visits in 2018, and GWMP was ranked the 7th most visited park in the nation with 7.3 million visits (NPS Stats 2018). Ecologically, the NCRN sits squarely within the drainage basin of the country's largest estuary—the Chesapeake Bay. Thus, forests in the region function as a water purification system for the Bay. Moreover, eastern deciduous forests in the Mid-Atlantic U.S. have been recognized for their high biodiversity and conservation importance (Olson and Dinerstein 2002;

Miller et al. 2018). In addition, urban forests sequester significant amounts of carbon (C) and are important for climate change mitigation (Nowak and Crane 2002). Finally, urban forests perform many other ancillary ecosystem services. For example, Long et al. (2019) recently showed that urban forest clusters in Raleigh, NC, similar to those found throughout the NCRN, helped protect neighboring trees in ornamental gardens from insect pests.

Importance of soils in the NCRN

By serving as a medium for plant growth, a habitat for microorganisms, a water-supply and purification system, an engineering medium, a modifier of the atmosphere, and a recycling system for nutrients and wastes (Weil and Brady 2017), soils are critical to the ecosystem services and ecology of the NCRN. Smith and Wilcock (2015) found that the sediment yields (a proxy for erosion) from forests in the Upper Patuxent watershed of MD were 28% of the yields from suburban landscapes and 35–64% of the yields from agricultural lands. Johnson and Richter (2010) described the important benefits of Mid-Atlantic forest soils for reducing the harmful effects of Pb and other heavy metals. Shen et al. (2016) discovered that soil pH in a Mid-Atlantic temperate forest in Virginia was an excellent predictor of invasive plant species. Szlavecz et al. (2011) studied the abundant earthworms in forest soils of the Piedmont plateau in MD, and found that they have significant ecological effects on leaf litter decay, soil fungi community dynamics, and even plant community selection (Szlavecz et al. 2011). Dixon et al. (1994) discovered that 64% of the total C in forest ecosystems of the contiguous U.S. was stored in the soil, whereas only 36% was contained in the vegetation, highlighting the carbon sequestration potential of forest soils in the Mid-Atlantic.

To measure the effect of soils on the forest ecosystems of the NCRN, the region began a soil inventory and monitoring program in 2007. The overarching goal was to integrate soils data with the existing vegetation, animal, and water monitoring programs to understand more completely ecosystem function. Accordingly, the NCRN developed protocols to measure soil chemical and physical properties across its 11 parks.

NCRN soil monitoring objectives

This report summarizes the soils data collected in the NCRN. The objectives are to:

1. Inventory and describe the physical and chemical characteristics of forest soils in the NCRN.
2. Provide baseline soils data to aid park managers and future forest soil monitoring in the NCRN.
3. Identify differences in forest soil variables between parks and the significance of these differences to overall soil quality and ecosystem function.
4. Highlight individual monitoring plots with outlier characteristic that might negatively affect ecosystem function or require further investigation.
5. Discuss future opportunities for soil monitoring in the NCRN.

Methods

Soil monitoring was conducted at the long-term forest vegetation plots described in Schmit et al. (2012). In total, 426 plots were sampled across the 11 park units of the NCRN (Table 1), which represents a density of 1 plot for every 62 ha of parkland.

Table 1. Parks and soil monitoring plots in the NCRN.

Park	Code	State	Physiographic Region	Number of Plots
Antietam NB*	ANTI	MD	Valley and Ridge	13
Catoctin Mountain Park	CATO	MD	Blue Ridge	46
Chesapeake & Ohio Canal NHP	CHOH	DC/MD	Coastal Plain/Piedmont/Valley and Ridge	67
George Washington Memorial Parkway	GWMP	DC/VA	Coastal Plain/Piedmont	28
Harpers Ferry NHP	HAFE	WV/MD	Blue Ridge/Valley and Ridge	21
Manassas NB Park	MANA	VA	Piedmont	19
Monocacy NB	MONO	MD	Piedmont	15
National Capital Parks – East	NACE	DC/MD	Coastal Plain	47
Prince William Forest Park	PRWI	VA	Piedmont/Coastal Plain	145
Rock Creek Park	ROCR	DC	Coastal Plain	19
Wolf Trap NP for the Performing Arts	WOTR	VA	Piedmont	6

* NB is a national battlefield; NHP is a National Historic Park; NP is a National Park.

Vegetation plots were laid out as a circle with a 15-m radius covering a total area of 707 m^2. For soil sampling, three 15-m long transects radiated out from the center of each plot at 120°, 240°, and 360° (Figure 2). In situ sampling efforts were divided into three components: 1) physical assays performed along the transects, 2) a soil profile description at the center of each plot, 3) a composite sample of O, A, and subsoil horizons taken from the top 15 cm of soil along the transects for soil chemical analyses.

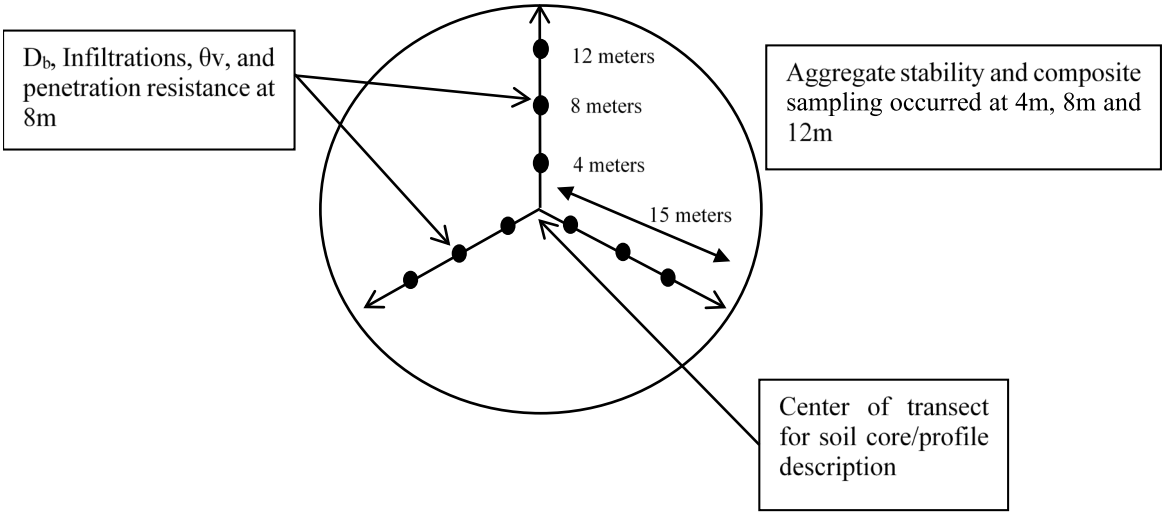

Figure 2. Layout of vegetation plots. Soil samples were taken along three 15-m transects, radiating from the center of the plot.

Field measurements: soil physical properties

Six physical measurements were performed at the 8-m mark (except for aggregate stability) along each of the three plot transects: bulk density (D_b), unsaturated infiltration, saturated infiltration, volumetric water content (θ_v), soil penetration resistance, and aggregate stability.

Bulk density (D_b)

Bulk density (D_b) was measured using a variation of the core method (Soil Survey Staff 2014a). In brief, loose leaves and duff were scraped off the top of the soil until the mineral soil was exposed. Metal rings of a known volume were then driven into the ground until their top was level with the surface of the mineral soil. The ring was then carefully excavated, and the soil shaved off flush with the top and bottom of the ring. The soil and coarse gravel fragments inside each ring were then placed in a sealed plastic bag and taken back to the lab for further analysis (see laboratory procedures section for additional details).

Infiltration and volumetric water content (θ_v)

A variation of the Natural Resources Conservation Service Infiltration Method was used to measure unsaturated and saturated infiltration (NRCS 1998). In brief, polyvinyl chloride (PVC) rings 15 cm in diameter and 15 cm high were pounded into the ground until 10 cm of the height of the ring were above ground and 5 cm were below ground. When present, loose leaf litter was removed from the surface of the soil on the inside and around the edges of the ring. Next, a two-pronged ECH_2O EC-5 capacitance moisture sensor (Decagon Devices, Pullman, WA) was inserted into the ground to measure θ_v (water volume/soil volume * 100) in the mineral soil (not O horizon) at 90º, 180º, 270º, and 360º around the edge of the ring. An average of the four measurements/ring was recorded as θ_v pre-infiltration (%).

After that, a thin layer of plastic was placed on the inside of the infiltration ring making sure to cover the entire surface area of soil and ring walls. 1 L water was gently added to the inside of the ring

covered in plastic wrap. The plastic wrap was then quickly removed from under the 1-L of water exposing the entire soil surface area inside the ring to water at the same time. As soon as the water hit the soil surface, a stop watch was started and only stopped when all water infiltrated into the soil. The time that it took for 1 L of water to fully enter the soil was entered into the following equation to calculate an unsaturated infiltration rate (cm hr^{-3}):

$$Unsaturated\ infiltration\ (cm\ hr^{-3}) = \frac{1L\ of\ Water\ (1000cm^3)/Infiltration\ Ring\ Area\ (cm^2)}{Unsaturated\ Ring\ Infiltration\ Time\ (s)/3600}$$

Saturated infiltration was measured within 5 minutes after unsaturated infiltration was completed. The same process that was used to measure unsaturated infiltration was repeated for saturated infiltration and the time that it took for 1 L of water to fully enter the soil a second time was recorded and used to calculate saturated infiltration (cm hr^{-3}) using this equation:

$$Saturated\ infiltration\ (cm\ hr^{-3}) = \frac{1L\ of\ Water\ (1000cm^3)/Infiltration\ Ring\ Area\ (cm^2)}{Saturated\ Ring\ Infiltration\ Time\ (s)/3600}$$

After infiltrations were completed, 30 minutes were allowed to elapse before the capacitance probe was used to take four readings on the inside of the ring where water infiltrated. The average of those readings was recorded as θ_v post-infiltration (%).

Soil penetration resistance

For penetration resistance, the NCRN began its monitoring program using a FieldScout SC900 electronic soil compaction probe (Spectrum Technologies Inc., Aurora, IL) that recorded penetration resistance in kilopascals (kPa) every 5 cm from the soil surface to a depth of 35 cm as the probe was pushed into the soil. This meter was used to monitor approximately one quarter of the plots, and the measurement was conducted on the inside of the infiltration ring after θ_v post infiltration was recorded.

For the rest of the plots, a variation of the cone penetrometer test and standard penetration test was used to determine penetration resistance in kilopascals (ASTM 1984, 1995). In summary, a drop hammer penetrometer was used to calculate penetration resistance at 5 cm intervals to 35 cm depth on the inside of infiltration ring after θ_v post infiltration was recorded. The drop hammer device consisted of a pole 165 cm tall with a pointed end for insertion into the ground. A cylindrical weight (2 kg) was manually slid along the pole from a fixed height in order to strike a peg to drive the pole into the ground. The number of times that the 2 kg cylindrical weight was dropped to drive the pole 5 cm into the ground was recorded and used in conjunction with the height that 2 kg weight slid along the pole and the weight of the cylinder (2 kg) to determine penetration resistance in kPa using the following three equation sequence to calculate first work (joules), then force (newtons), then resistance (kPa):

$$Work\ (joules) = number\ hammer\ hits \times gravity\ \times height\ \times mass\ striking\ weight$$

$$Force\ (newtons) = \frac{work\ (joules)}{distance\ penetrometer\ traveled\ in\ soil\ (m)}$$

$$Penetration\ resistance\ (kPa) = \frac{Force\ (newtons) \times 10}{\pi(radius\ of\ pole)^2}$$

Aggregate stability

At 4, 8, and 12 m along each transect, leaf litter and O horizon was removed from the soil surface before a trowel was used to gently remove a soil aggregate 0.5–1 cm in diameter from the top 5 cm of mineral soil surface (9 aggregates/plot). The aggregates were placed on a metal mesh screen attached to a small disk made from 1-cm PVC pipe. These screens were placed into tackle box for transport back to the Center for Urban Ecology. Aggregates were collected for approximately half of the plots in the NCRN because of the difficulty of transporting samples back to the lab without breaking them.

Field measurements: soil profile description

A bucket auger was used to excavate a soil core to a depth of 100 cm (when possible) within a 1-m radius of the center of each plot. The soil was laid out horizontally on a plastic sheet with ruler markings in centimeters corresponding to the depth of the sample. When bedrock was encountered less 100 cm from the soil surface, up to 3 more cores were excavated adjacent to the center of the plot, and the deepest core was used to complete a soil profile description. The description was carried out according to guidelines from the Natural Resources Conservation Service (NRCS, 2012) and consisted of the master and subordinate horizon sequence with lower boundary depths, the textural class of each horizon and clay percentage (determined by feel), the predominant matrix color using the Munsell color scheme for each horizon, the presence and depth of redoximorphic (redox) features in a horizon (depletions and concentrations), and a visual estimation of coarse fragments (rock and mineral fragments >2 mm diameter). Approximately 75 g of soil was taken from each horizon, placed in a sealed plastic bag and transported back to the Center for Urban Ecology for further processing.

Field measurements: soil composite sampling

At 4, 8, and 12 m from the center of the plot along each of the three 15-m long transects, a soil probe was used to collect a sample to a depth of 15 cm (9 probe points total/plot). The soil sample at each probe point was then separated into O horizon, A horizon, and Subsoil horizon (defined here as any soil below the A horizon) components (when those horizons were present), and each fraction was placed into a separate container. This process was repeated at all 9 locations, and then a composite sample of O, A, and Subsoil horizons was made by thoroughly mixing the soil from the 9 probe points. The O, A, and subsoil composite samples were sealed in a plastic bag and transported to the Center for Urban Ecology for further processing.

Laboratory procedures

Bulk density (D_b)

D_b samples were weighed fresh, and then the soil was passed through a 2 mm sieve. Any coarse fragments >2 mm in diameter that did not pass through the sieve were weighed. The sieved soil was then placed in a 105ºC oven for 24 hours and re-weighed (weight dry soil). The volume of the coarse

fragments in D_b samples was calculated using the following equation which assumes a coarse fragment density of quartz—2.65 g cm^{-3} (the most common mineral in the NCRN):

$$Volume\ of\ coarse\ fragments\ (cm^3) = \frac{weight\ coarse\ fragments\ (g)}{Density\ of\ coarse\ fragments\ (2.65\ g\ cm^{-3})}$$

D_b was calculated accounting for the volume of coarse fragments in the D_b rings according to this equation:

$$D_b\ (g\ cm^{-3}) = \frac{weight\ dry\ soil\ (g)}{volume\ of\ ring\ (cm^3) - volume\ of\ coarse\ fragments(cm^3)}$$

Aggregate stability

Aggregate stability was measured using a variation of the slake test (NRCS, 2019) and given a stability class rating of 1–6. Briefly, aggregates were air-dried at the lab before the mesh screen and 1-cm PVC apparatus that they rested on was submersed in distilled water for a total of 5 minutes. Soil stability was rated as a function of the time that it took for the aggregate to disintegrate. If 50% of the aggregate disintegrated with 5 seconds after insertion in water, the aggregate was rated as a 1. If 50% was gone between 5–30 seconds, the aggregate was a 2. At the end of 300 seconds (5 minutes), if >50% was gone, the aggregate was a 3, but if 50–75% of the aggregate remained, the stability class was 4, and for 75–99% of the aggregate remaining after 5 minutes, the class was a 5. Aggregates that showed no signs of disintegration within 5 minutes were classified as a 6.

Chemical analyses

Profile horizon samples and composite O, A, and Subsoil samples were air-dried on paper plates and passed through a 2-mm sieve before a subsample of 50–100 g was sent for chemical analyses to the University of Georgia Agricultural and Environmental Services Laboratories (AESL) Soil, Plant, and Water lab (SPW). Total carbon (C) and total nitrogen (N) were measured by high temperature combustion at 1350ºC using an Elemental Combustion Analyzer, Model Vario Max (Langenselbold, Germany). The Mehlich-1 soil test extractant (Mehlich 1953) was used to extract plant macronutrients (P, K, Ca, Mg, Mn, and Zn), plant micronutrients (Fe, Zn, Cu, Mo), and soil contaminants (Cd, Cr, Pb). The Mehlich-1 extraction was followed by analysis on an Inductively Coupled Plasma Spectrograph (ICP). All extractable levels were expressed as mg element per kilogram soil (mg kg^{-1}). Soil pH was measured on an automated analyzer with direct titration capabilities using a 1:1 soil:0.01 M CaCl2 suspension. An indirect measurement of cation exchange capacity (CEC) was determined by adding the milliequivalents of bases (Ca, Mg, K, and Na) present in the Mehlich-1 extract and the milliequivalents of exchangeable hydrogen as determined by direct titration with 0.023M $Ca(OH)_2$ and the units were expressed as milliequivalents per 100 grams of soil (Georgia Cooperative Extension 2008). The percent base saturation (BS) in the soil was calculated as the ratio of Ca, Mg, K, and Na to that of CEC.

Data analysis

A thorough quality analysis/quality control (QA/QC) process was initiated for the NCRN soils dataset. Raw data were graphed and compared to ratios of known correlated soil physical and chemical variables to identify outliers and possible artifacts. Outliers or artifacts were excluded or

corrected (if possible). Corrections were informed by field notes recorded at the time of data collection.

For the analysis presented here, all data were grouped together and analyzed by park. Organizing physical and chemical properties by physiographic region, geology, or parent material (the material that the soil formed from) would undoubtedly have yielded more ecologically meaningful insights, but the rationale for choosing to categorize by park was based on the chief objective of the I&M Program—to guide *park* management using science. In addition, this report is primarily an inventory of the soils in the NCRN, and parks served as a convenient framework to categorize the data.

The NRCS Web Soil Survey (Web Soil Survey 2019) was used to determine the soil series at each plot using the GPS coordinates of the sampling site. When more than one possible soil series was present, the augered soil profile description was compared to the USDA's Official Soil Series Descriptions (USDA 2019) to determine the most probable soil series. A list of soil series in the NCRN can be found in Appendix D. At the beginning of the "Park overviews" section, a general survey of important NCRN soil characteristics is given (Table 2): the number of soil series in each park, the relative depths of soils across the region, the presence or absence of three important soil horizons across the region (O, Bt, Bw), and the number of poorly drained soils.

Kruskal-Wallis (non-parametric) ANOVAs were used to determine statistically significant differences ($p<0.05$) between parks for the soil physical properties: D_b, infiltration rates, θv, penetration resistance, and aggregate stability. Dunn's multiple comparisons post hoc test was performed to identify which park/s were significantly different. Plots where the FieldScout SC900 was used to collect penetration resistance data were not double sampled with the drop hammer method, so a true comparison of the methods is impossible in this report. However, a T-test was used to determine if plots with penetration resistance values from the FieldScout SC900 were significantly different from plots with penetration resistance values using the drop hammer method. Finding no significant differences, data from both measurement methods were analyzed together.

Descriptive statistics (mean ± standard deviation) were calculated for all chemical characteristics (macronutrients, micronutrients, contaminants, pH, CEC, BS), clay content, and percentage of coarse fragment by master horizon (O, A, E, B, C) for each park and are shown in tabular form in the "Park Overviews" section. The distribution of these data (mean ± standard error of the mean {SEM}) throughout all parks of the NCRN are shown in figures in the "Soil physical properties" section (clay content and coarse fragments) and in the "Soil chemical properties" section (all other data).

To account for subordinate horizons with the same master horizon designation (e.g., Bt1, Bt2, Bt3 or Ap1, Ap2), a weighted average was used that accounted for the thickness of each of the subordinate horizons in relation to the thickness of the entire master horizon. For example, a profile description might contain a 13-cm thick Bt1 horizon, a 23-cm thick Bt2 horizon, and a 33-cm thick Bt3. The entire thickness of the B horizon, therefore, was 69 cm, and a weighting factor of 0.19 (13/69) was calculated for the Bt1, 0.33 for the Bt2, and 0.48 for the Bt3. These weighting factors were then multiplied by the quantitative chemical data for each of their respective horizons and then summed to give the weighted average of the entire B horizon. The "Horizon midpoint" designation in the "Park

Overviews" data tables is the depth from the soil surface where the midpoint of the entire master horizon (the sum of the Bt1, Bt2, Bt3 to use the example above) occurred.

Chemical data for the A horizon composite samples is shown separately (Composite A samples are referred to in in figures as "A comp," and profile samples are "A prof."). The rationale to analyze profile A and composite A samples distinctly was based on two reasons. First, the composite samples accounted for the spatial variability across the plot, whereas profile samples were taken from one point at the center of the plot. Second, composite sampling was confined to the top 15 cm of the soil (i.e., If an A horizon continued deeper than 15 cm in the probe, nonetheless, only the portion of the A horizon from 0–15 cm was included in the sample.), but profile A samples could encompass an Ap horizon to a depth of 30+ cm. Thus, "A comp" samples more closely captured the surface A horizon development from the reforestation of plots under NPS management, and "A prof" samples contained a mixture of legacy A horizon from agriculture and more recent carbon accumulation from afforestation. Composite O horizon samples were sent for chemical analysis in lieu of profile O samples. The reason was that O horizons were typically 2 to 5 cm thick, and not enough sample could be obtained from the profile core. In addition, O horizons were sometimes present at certain transects in the plot but absent from the center point. The "Horizon midpoint" for O horizons was recorded from the profile core, however, when "Horizon midpoint" is blank, it indicates that an O horizon was not present at the center of the plot. Subsoil composite samples were not analyzed.

Regression analysis was used to evaluate relationships between soil properties. Total C, pH, and clay percent (often described as master variables because they affect so many other soil properties) were chosen as predictor variables for all other chemical variables.

Finally, Kruskal-Wallis ANOVAs were used to determine statistically significant differences ($p<0.05$) between parks for the chemical variables in each master horizon, e.g., significant differences between parks examining the O, A profile, A composite, E, B, and C horizons separately. When significance was established, Dunn's multiple comparisons post hoc test was employed to identify which park/s were significantly different.

Results and Context

Results are subdivided into six subsections: 1) *Soil physical properties* describes the coarse fragments, clay percent, bulk density (D_b), bulk density hybrid (D_{bH}), infiltrations, volumetric water content (θ_v), and penetration resistance; 2) *Soil chemical properties* covers macronutrients, micronutrients, pH, base saturation, cation exchange capacity, and contaminants; 3) *Regression analysis* outlines the results of a regression analysis examining the relationship between three master soil variables—C, pH, and clay percent—and all other chemical variables; 4) *Statistical differences by horizon* details significant chemical variable differences horizon by horizon among the parks; 5) *NCRN overview* summarizes the NCRN's soil series, relative soil depths, drainage and other horizon characteristics; and 6) *Park overviews* presents a park-by-park analysis of horizon depths, clay content, coarse fragments, and chemical characteristics. All results are preceded by the definition of the measured property and a brief description of its relevance to natural resource monitoring and management within the NCRN. A complete list of soil terminology used in this report is found in Appendix A.

Soil physical properties

Coarse fragments and clay percent

Coarse fragments are solids >2 mm in diameter, while the fine earth fraction consists of soil particles <2 mm in diameter. Four types of coarse fragments are found in the NCRN, in order of their size from smallest to largest: 1) Gravel (GR) – Coarse fragments that are 2 to 75 mm along their greatest diameter; 2) Cobbles (CB) – Rounded coarse fragments that range from 75 to 250 mm along their greatest diameter; 3) Channers (CH) – Flattened coarse fragments that range from 75 to 250 mm along their greatest diameter; 4) Flags (FL) – Flattened large stones ranging from 150 to 380 mm along their greatest diameter. The abundance of coarse fragments in soils are a function of the parent material (e.g., soils formed from carbonate rocks will be very different from those formed from acidic shales.), topography (e.g. soils at the bottom of a mountain often have many coarse fragments that moved down hill), age (e.g., older soils frequently have fewer rocks because they have had time to break down into soil.), and climate (e.g., colder areas have slower chemical and biological reaction rates which means that coarse fragments often are more prevalent in colder environments). The relative abundance of coarse fragments does not necessarily have any effect on the fertility of the soil or the ability to support vegetation. However, coarse fragments do typically alter water flow and water holding capacity in soils (see Infiltration section below).

Soils are composed of three particle size classes all <2 mm in diameter: sand, silt, and clay (from largest to smallest, respectively). Clay particles have a diameter <0.002 mm. With an enormous surface area (a fixed mass of clay particles can have a surface area hundreds of thousands of times greater than the same mass of sand particles), the clay percentage has a very strong effect on many physical and chemical soil processes, including bulk density, penetration resistance, water infiltration and storage, carbon sequestration, and fertility. However, the chemical composition and morphology of clay particles can differ greatly, ranging from clays that hold an enormous quantity of plant nutrients to clays that are very low-charge and that have a low inherent fertility, depending on the

parent material of the soil. Often clay soils in warmer, wetter regions (e.g., the NCRN) would be expected to have weathered, low-fertility clays.

Figure 3 shows the distribution of coarse fragments and clay throughout the profile from the A to C horizon. MONO contained the highest percentage of coarse fragments by volume (27, 65, and 38% in the A, E, and B horizons respectively), and MANA contained the lowest (2 and 4% in the A and B horizons respectively). The other two parks with a predominance of mountain soils, CATO and HAFE, had the second and third highest coarse fragment percentages respectively in both A and B horizons. CHOH, GWMP, NACE, and PRWI (in addition to MANA) all contained ≤ 10% coarse fragments in their A and B horizons. There was a large amount of intra-park coarse fragment variation, and with the exception of MONO, HAFE, and CATO, the standard deviation in each park was greater than the mean (see data tables in Appendix B). Nevertheless, the ANOVAs showed that the differences between MONO, HAFE, CATO and the aforementioned parks with ≤ 10% coarse fragments were mostly statistically significant in the A and B horizons (Appendix C). MONO contained significantly more coarse fragments than PRWI in the E horizon and there were no differences between parks in the C horizon.

It should be noted that four parks—ANTI, CATO, GWMP, MANA—had no E horizons and consequently do not appear in Figure 3. Moreover, three parks—HAFE, ROCR, and WOTR—had 3 or fewer plots/park with an E horizon (HAFE had 3 plots; the other parks had 1). We therefore decided to exclude them from statistical analyses and subsequent figures because too few replicates generate a low power to detect statistical differences. Nevertheless, the E horizon average for HAFE and values for ROCR and WOTR can be found in the data summary tables in Appendix B. There were also no C horizons in ANTI and HAFE, and 2 or fewer C horizons in CATO, MANA, MONO, and WOTR. Therefore, only CHOH, GWMP, NACE, PRWI, and ROCR's C horizons are shown in Figure 3. (See Appendix B for the missing park values.)

From surface to base of the soil profile (A to C horizon), clay percentage trended the same way in all parks of the NCRN. The pattern was for a clay decrease from A to E horizon before increasing sharply from E to B and then tailing off from B to C horizon. Opposite of its coarse fragment percentages, MANA had the highest clay percentage of any park in the NCRN. It contained 23% clay in the A horizon and 33% in the B horizon. HAFE had the lowest clay percent: 11 and 16% in A and B horizons respectively. After MANA, PRWI and ANTI had the next highest clay percentages in their A and B horizons. ROCR was the only park other than HAFE to have <20% clay in its B horizon, and CATO had the second lowest clay percentage in its A horizons. The ANOVAs showed that the differences between MANA, PRWI and CATO and HAFE were statistically significant in the A horizon, and ANTI, PRWI, and MANA all had significantly more clay than HAFE and ROCR.

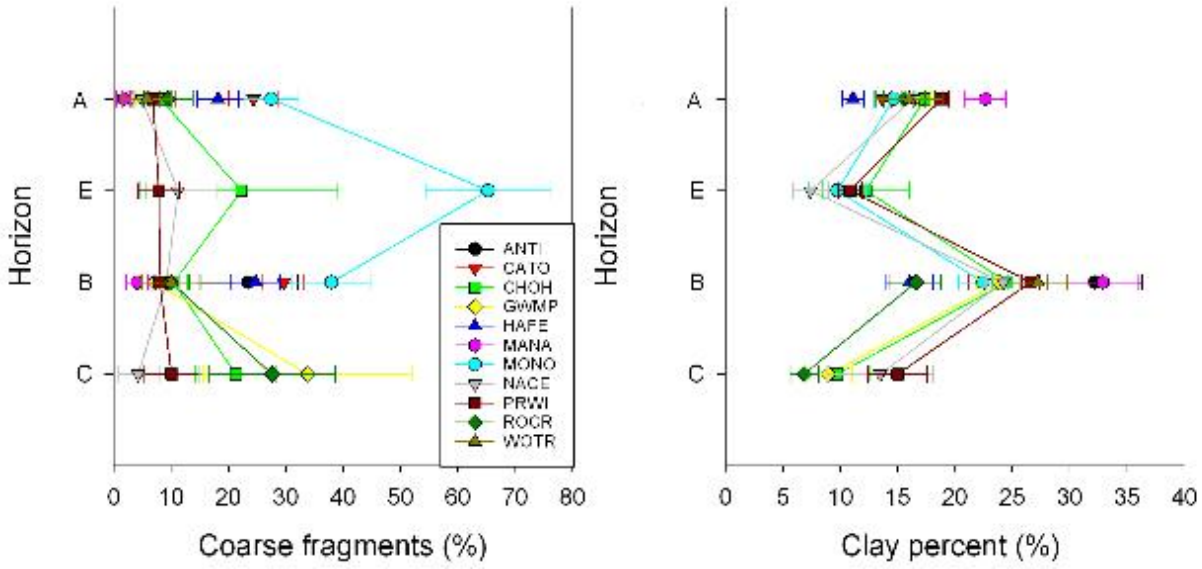

Figure 3. Distribution of coarse fragments and clay percent by horizon in all parks of the NCRN. Errors bars represent standard error of the mean (S.E.M.) throughout all figures.

Bulk density (D_b)

D_b is the dry weight of the soil fine earth fraction divided by the entire volume of that fine earth fraction (including pore spaces). D_b differs from particle density (D_p) because D_p measures the dry weight of the fine earth fraction divided by the volume of fine earth fraction (without pore spaces). D_b can be used to calculate the pore space of the soil because soil scientists frequently assume a fixed particle density (D_p) of 2.65 g cm^{-3} for the soil solids (mainly quartz-based particles east of the Mississippi). So, percent pore space = $1 - D_b/D_p$. In addition, D_b is an indirect measure of compaction. The higher the D_b value, the fewer pores there are in that volume of soil and thus the more compacted the soil. D_b values between 1.45 g cm^{-3} for clays and 1.85 g cm^{-3} in sandy soils will typically start to impede root growth and detrimentally affect plant growth (Weil and Brady 2017).

D_b values across the NCRN were typical of uncultivated loamy A horizon forest soils (0.8 to 1.2 g cm^{-3}), described in Weil and Brady (2017). This suggests that forest habitats of the NCRN parks are not experiencing excessive foot traffic or other forms of compaction. Moreover, it also indicates that soil C levels (which are generally inversely related to D_b) are adequate to maintain lighter low-density soils in the NCRN.

All parks except WOTR had D_b values <1.0 g cm^{-3} in the top 15 cm of the mineral soil (Figure 4). The only park that was notably below typical D_b mineral forest soils was CATO (0.49 g cm^{-3}), which was significantly different from all other parks. The low values undoubtedly arose from the high levels of soil C (see figure in Soil chemical properties section) which promotes strong structure and numerous soil pores. HAFE, the only other park comprised of mountain soils, also had a lower D_b (0.75 g cm^{-3}) than CHOH, MANA, and WOTR.

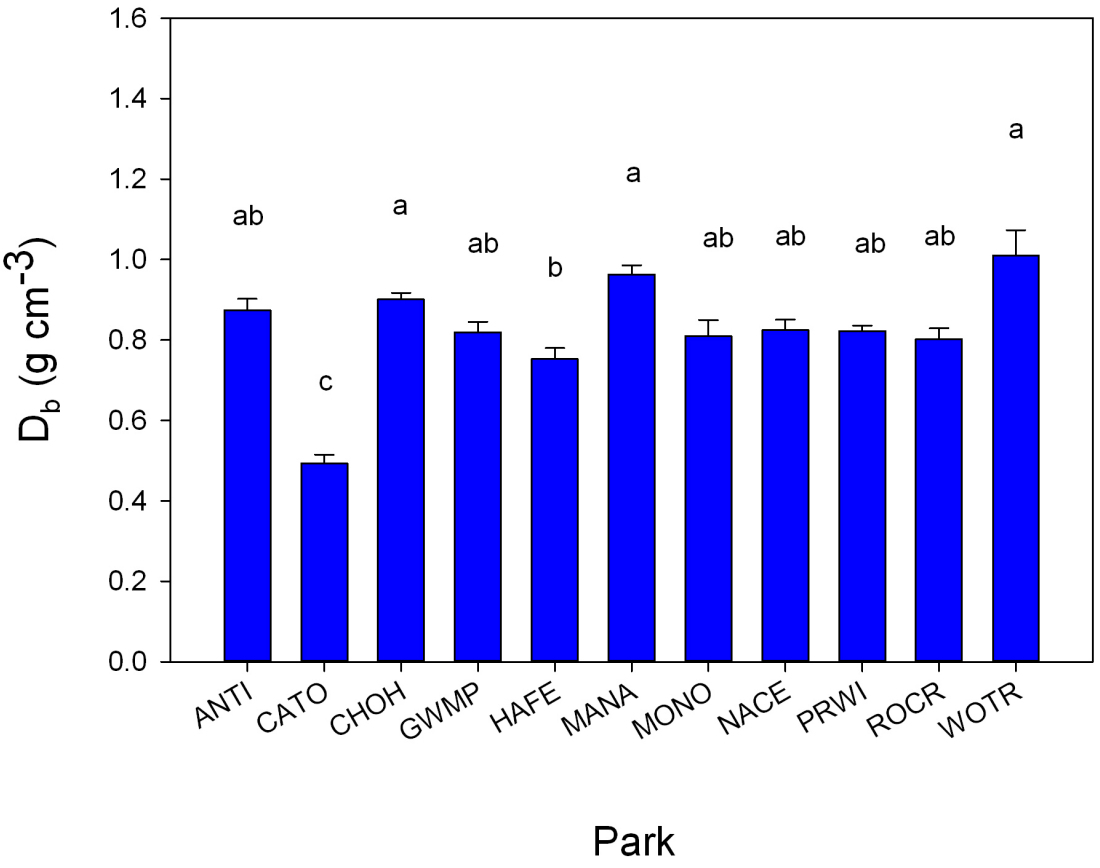

Figure 4. D_b in the eleven parks of the NCRN. Parks that share the same letter are not statistically different.

Infiltration

Unsaturated infiltration describes the rate at which water enters a soil, given that soil pores are not all filled with water (or in the case of this work, in soils that were not previously wetted by the soil tester). Saturated infiltration measures the rate water enters a soil that has been previously wetted and assumes, therefore, that all soil pores are filled with water. Saturated infiltration is a proxy for saturated hydraulic conductivity, when water flows through macropores (soil pores >0.08 mm in diameter).

The unsaturated infiltration rate at all plots was highly dependent on the soil moisture at the time of sampling. (Very dry plots would have very different infiltration rates than a plot with the same texture but higher moisture level.) Consequently, the purpose of the unsaturated infiltration was primarily to standardize moisture conditions across plots and ensure that all soil pores were filled with water before saturated infiltration could occur. The saturated infiltration rate is fundamentally a function of the size, abundance, and shape of the soil macropores which is dependent on soil texture, structure (strength of the soil aggregates), and coarse fragment content. Soils with high percentages of coarse fragments typically have faster infiltration rates (Chow et al. 2007), and soils with higher

clay contents (all other factors held constant) have slower infiltration rates. Carbon content is related to soil structure, and soils with high total C typically have more pronounced aggregates, greater amounts of macrofauna (e.g., earthworms which create macropores), larger macropores, and thus faster infiltration rates all things being equal.

In the NCRN, infiltration is especially important to monitor because of the number and duration of high rainfall events in the area. The opposite of infiltration is runoff, which can lead to erosion, eutrophication in the Chesapeake Bay, loss of vegetation, and infrastructure damage potentially costing parks millions of dollars in cleanup and repair fees.

Unsaturated infiltration was 156% faster (averaged across all parks) than saturated infiltration (282 v. 126 cm hr^{-1} respectively). Though unsaturated infiltration is dependent on soil moisture at the time of measurement, there was a positive linear relationship between the two infiltrations (r=0.91). Relatively slow saturated infiltrations were preceded by slow unsaturated infiltrations (Figure 5). CATO had a significantly faster saturated infiltration rate (266 cm hr^{-1}) than all other parks except for PRWI and WOTR. (It should be noted that WOTR, with its small number of samples brought down the statistical power to detect significant differences.) WOTR, MANA, ANTI, GWMP, and HAFE were all characterized by particularly slow saturated infiltrations of <100 cm hr^{-1}, which were approximately three times slower than CATO's. The fast infiltration rates in CATO can be explained both by the high levels of soil C (see figure in Soil chemical properties section) which create macropores, the shallowness of the soils (Table 2), and the high numbers of large rocks in the soil. Chow et al. (2007) found that larger pore sizes were more prevalent in soils with 30% coarse fragments than with no coarse fragments and consequently, that water flowed through the stony soils much faster than through the soils without stones. In contrast, parks such as ANTI and MANA had the least amount of coarse fragments (Figure 3) and the highest clay percentages in the region which undoubtedly contributed to their slower infiltration rates.

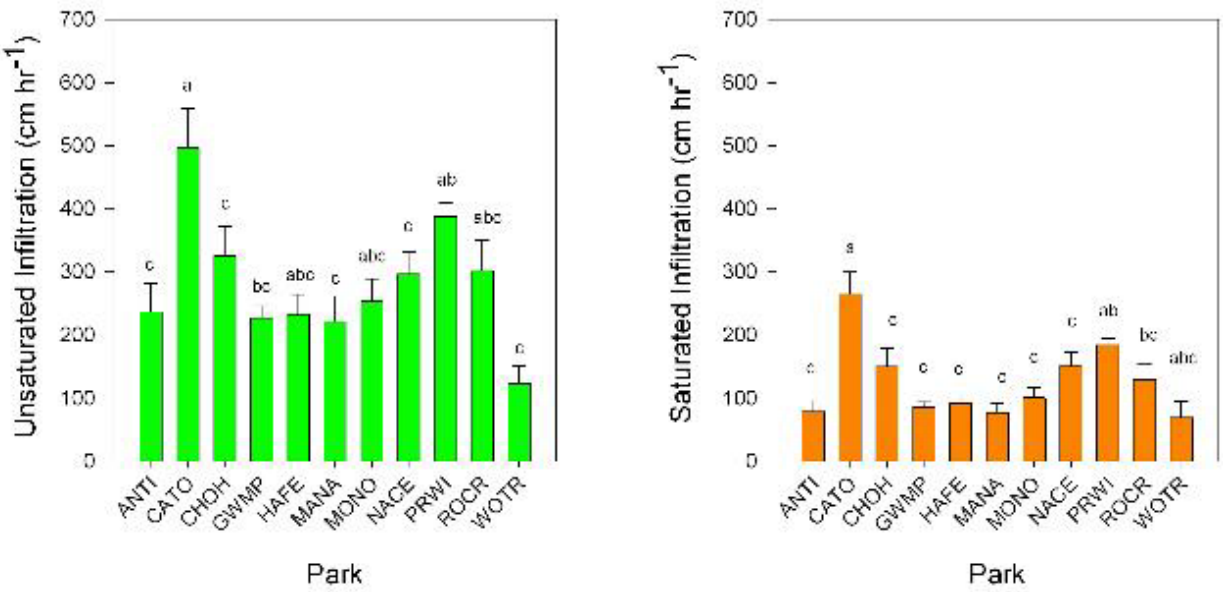

Figure 5. Unsaturated and saturated infiltration across the NCRN parks. Parks with values that are significantly different do not share the same letter over bars.

Volumetric Water Content (θ_v)

Volumetric water content (θ_v) measures the volume of water in a specific volume of soil (expressed as the percent of a volume of soil that is occupied by water). Like infiltration, θ_v is a function of the size, shape, and abundance of soil pores. Unlike infiltration, many of the factors that increase the abundance of macropores and thus infiltration rate, have the inverse effect on θ_v. For example, water is held more tightly (i.e., does not flow through the soil) in small micropores (pores <0.08 mm in diameter) with a lower matric potential. Soil textures with higher percentages of clay, therefore, have a higher percentage of micropores and thus higher water content, all other factors remaining constant.

Plants take up water according to energy status (potentials), and two soils that have the same θ_v can have very different potentials based on their texture. Thus, θ_v is not ipso facto an indicator of whether plants are well watered. However, θ_v is very useful for understanding the water holding capacity of NCRN soils—i.e., the potential of the region's soils to serve as a sponge after heavy rainfall events. Moreover, θ_v is important for gauging how quickly water might be released to vegetation after infiltration events have occurred.

Averaged across all parks, θ_v post-infiltration was 44% greater than θ_v pre-infiltration (29 compared to 20%, respectively; Figure 6). Like unsaturated and saturated infiltration, θ_v pre and post infiltration shared a positive linear relationship (r=0.74). Parks with relatively lower θ_v pre-infiltration had lower θ_v post-infiltration. However, the magnitude of the difference between parks was much less for θ_v than for infiltration. Only a 6% gap in θ_v separated the park with the lowest post-infiltration values (PRWI with a 26% θ_v average) from the park with the highest (MANA with 31%). Similarly, 7% θ_v separated PRWI from MANA's pre-infiltration rates (17 and 24% respectively). CHOH, MANA, and

ROCR were statistically greater than CATO and ROCR pre-infiltration. Post-infiltration, only MANA was significantly greater than HAFE, and CHOH,

Post-infiltration values at MANA and NACE were significantly greater than PRWI. MANA has much more clay in its soils than PRWI, and NACE has fewer coarse fragments which undoubtedly contributed to the differences. All other parks were not statistically different.

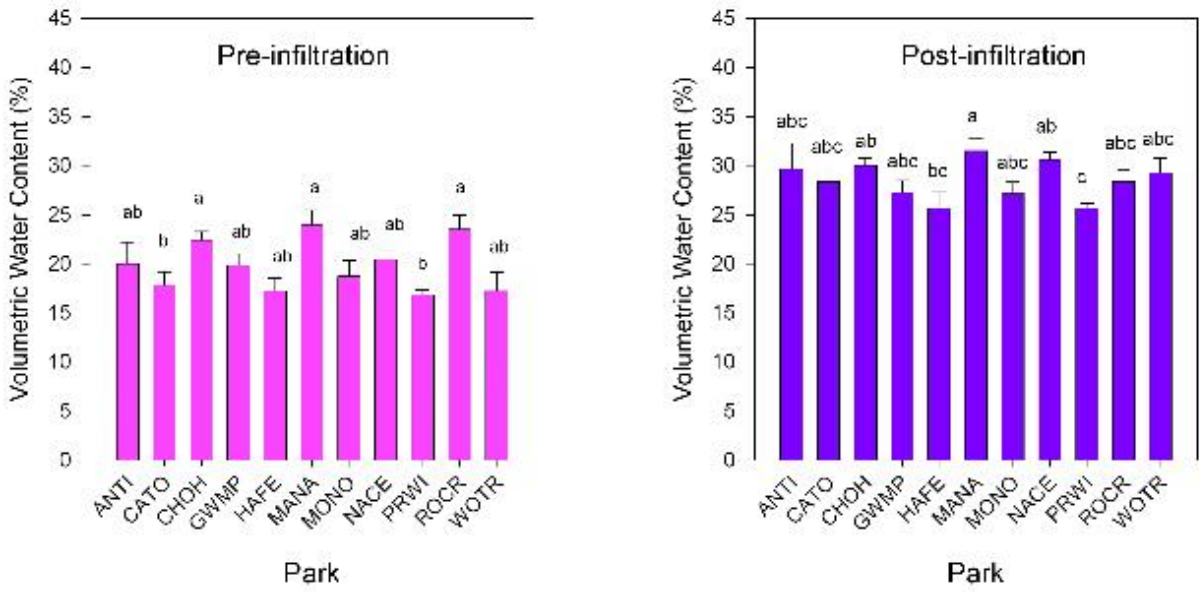

Figure 6. θ_v pre and post-infiltration in the parks of the NCRN. Parks with values that are significantly different do not share the same letter over bars.

Penetration resistance

Penetration resistance, measured in kilopascals (kPa), is a measure of the ease of penetrating the soil with a narrow rod capped by a cone-shaped head. This test is an indirect measure of soil compaction and can indicate how quickly water can enter a soil or the corollary—whether water might run off the surface and cause erosion—or whether plant root growth will be impeded. High-clay soils with tighter bonds between particles are typically more resistant to penetration than sandy soils. In the NCRN, clay percentages typically increased from the A to B horizon which likely drove the observed increases in penetration resistance with depth (Figure 7). However, coarse fragments also impede penetration, and soils with a preponderance of coarse fragments can increase resistance. With its positive effect on soil structure, carbon content is inversely related to penetration resistance.

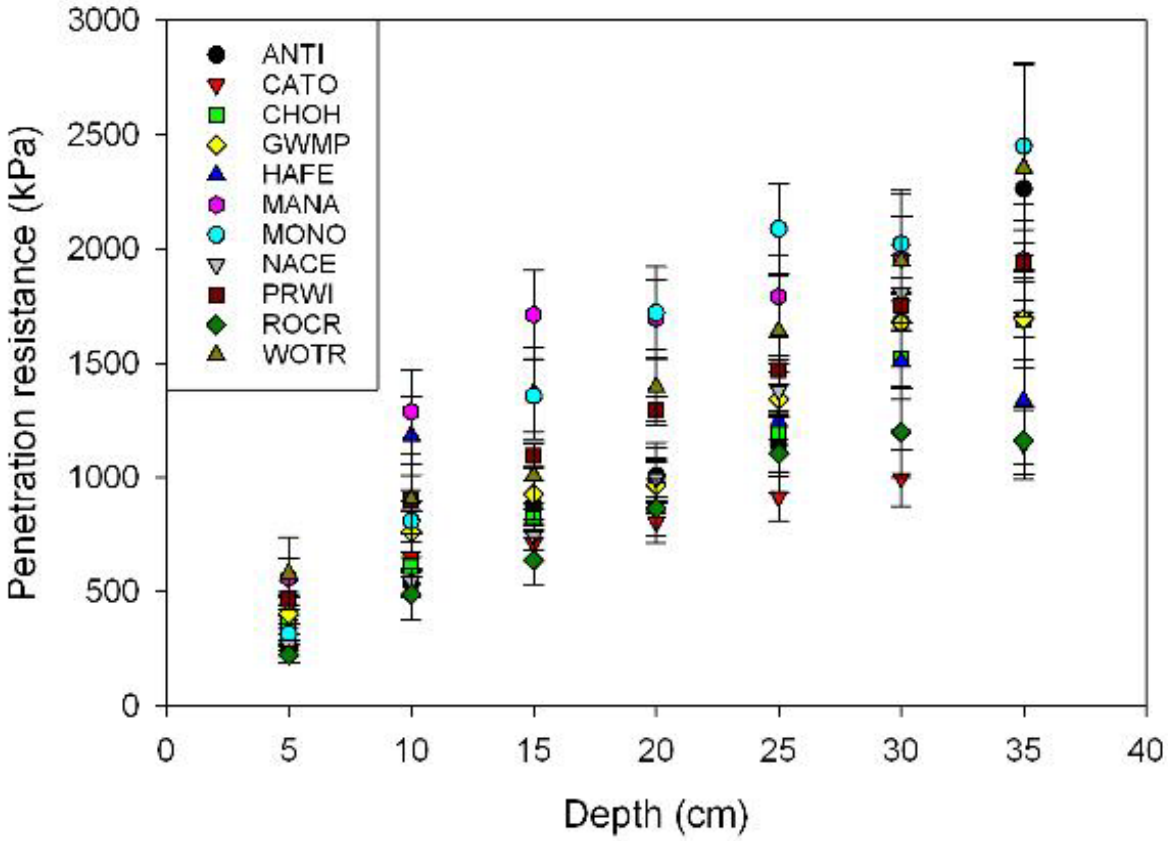

Figure 7. Penetration resistance showing a positive linear relationship with depth in the parks of the NCRN.

Across the NCRN, penetration resistance increased linearly with depth (r=0.99) from 5 to 35 cm below the soil surface (Figure 7). Near the surface at 5 cm depth, the region's average penetration resistance was 397 kPa, and at 35 cm depth it was 1814 kPa. MANA, MONO, or WOTR had the greatest penetration resistance from 5 to 30 cm depth, and HAFE also had relatively high values in the top 15 cm (Figure 8). MANA and MONO had the highest clay and coarse fragment percentages, respectively, which likely is responsible for their higher penetration resistances. ROCR or CATO had the least penetration resistance throughout the profile, and ANTI and NACE also had low resistance values in the top 15 cm. Though CATO had large amounts of coarse fragments, its fragments were generally large stones with many large pores between the rocks. Thus, the probe was able to penetrate easily between rocks into large pores spaces. ANOVAs showed that MANA typically had statistically greater penetration resistance than CATO, CHOH, NACE and ROCR. (Again the hypothesis is that this is caused by the high clay contents at MANA.) Moreover, in the top 20 cm NACE, and ROCR had significantly less penetration resistance than GWMP, HAFE and MANA, and from 15 cm down, CATO had less resistance than MANA, MONO, and PRWI.

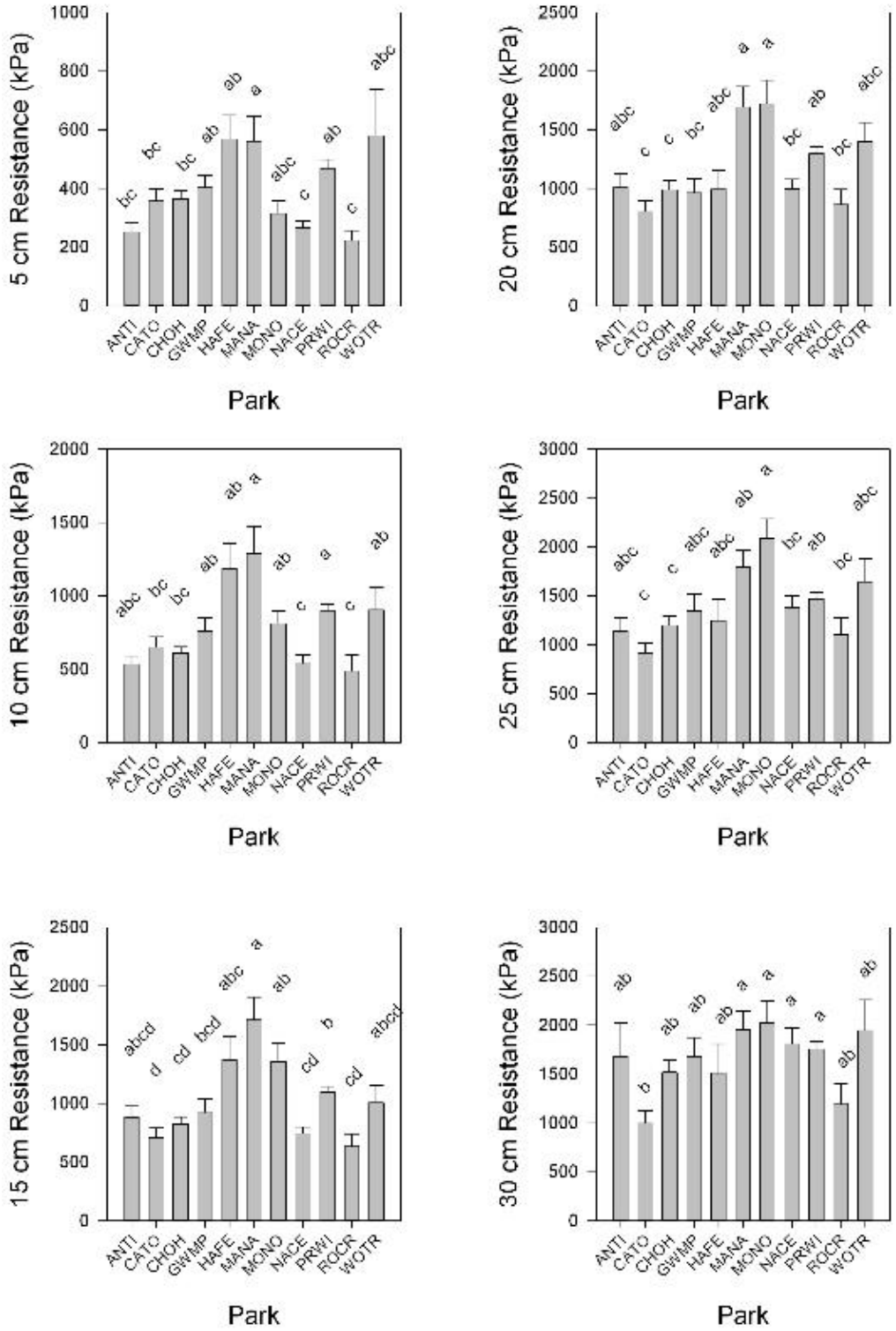

Figure 8. Differences in penetration resistance between parks from 5 to 30 cm depth. Parks with values that are significantly different do not share the same letter over bars.

Aggregate stability

Aggregate stability is an important test of the cohesion of an aggregate (a mass of soil particles held together in a cohesive shape) from the surface of the soil. If the aggregate falls apart quickly after being placed in water, it is poorly cohesive. Aggregate stability is an important measure of erosion resistance. When soils have strong aggregates, they do not erode easily. Aggregate formation is typically heavily influenced by soil C content and the turnover of organic matter. In addition, aggregates can be broken up as a result of human or mechanical traffic disturbing the soil surface. Thus, aggregate stability can indicate park managers about specific areas of a forest that might be enduring a heavy volume of foot traffic, or that have low organic matter inputs, or be subject to some other stressor.

Aggregate stability values were not significantly different between parks (data not shown). The park averages were between 5.6 and 6.0 (6 being the highest value possible for this parameter). For aggregate stability descriptive statistics by park unit, see Appendix B, table B13. ANTI had the largest amount of variation between plots (an average aggregate stability of 5.6 ± a standard deviation of 1), whereas all of WOTR's plots contained aggregate stability values of 6. The following 9 plots had aggregate stabilities <3 indicating that the aggregates slaked (fell apart) very quickly when immersed in water: NACE-0304, CHOH-1148, NACE-0621, ANTI-0207, CATO-0035, ROCR-0186, CHOH-1148, MONO-0061, and PRWI-0707. These plots should undergo further scrutiny to determine if human traffic or other causes are endangering the overall soil health in those plots.

Soil chemical properties

Total carbon and macronutrients

Total carbon (C) is a measure of the grams of C per gram of soil on a dry weight basis. Carbon is critical to the functioning of soils. Structurally, it helps soil aggregate; it increases pore space and water content thus reducing compaction; it is a fuel for microorganisms; it increases the cycling of nutrients; it is the backbone of many large organic molecules that other elements can attach to. Macronutrients are chemical elements that plants need in large quantities for proper growth. There are six inorganic macronutrients: N, P, K, Ca, Mg, and S.

Figure 9 shows the distribution of total C and macronutrients (except S) by horizon. One park, WOTR, had no O horizons in any of their plots and consequently O horizon data do not appear in the figure. Moreover, four parks—ANTI, MANA, MONO, ROCR—had two or fewer plots/park with an O horizon (MONO had 2 plots; all the rest had one.). We therefore decided to exclude O horizon data for these parks' statistical analyses and subsequent figures because of low power to detect differences. Nevertheless, their values can be found in the data summary tables in Appendix C. The E and C horizons were excluded from analyses, and the reasons for their exclusions can be found in the section describing coarse fragments and clay percent.

Macronutrient concentrations generally decreased with depth throughout parks of the NCRN (Figure 9) which is common in forest soils (Johnson and Lindberg 1992; Weil and Brady 2017). Four clear exceptions were found: P and Mg were highest in CHOH's C horizon; MONO's P concentration in the E horizon was greater than other horizons; and Mg concentration in MANA's B

horizon was higher than other horizons. The aberrations in CHOH and MONO can be explained by one outlier plot with extremely high nutrient concentrations in each of those parks (discussed in more detail in the CHOH and MONO park overview sections), whereas MANA's increasing Mg with depth is attributable to the particular parent materials from which those soils formed (further discussion in the MANA park overview section).

Averaged across all parks, total C in the O horizon (30.5%) was 5.5 times greater than total C in the A horizon composite samples (5.5%). The magnitude of the decrease in total C between the A composite and B horizon samples was even greater than from O to A. The B horizons had 7 times less total C (0.79%) than the A composites (5.5%). The NCRN average total C in the C horizons was 0.48%. Interestingly, total C in the A profile horizons (3.7%) was 32% less than in the A composite horizons. For all macronutrients except P, the A profile samples contained 25–31% less of the nutrient than the A composite samples. This suggests that in the surface horizons even a slight change in depth can have a measurable impact on soil chemistry.

Total N was distributed very similarly to total C. The O, A composite, A profile, E, B, and C horizons contained 1.28, 0.30, 0.22, 0.06, 0.06, and 0.03% total N respectively. Extractable K, Mg, and Ca did not experience a decrease by depth to the same proportion as total C and N. However, there was at least a threefold drop in extractable K from O to A and another threefold drop from A to B horizon. There was also a threefold drop in Ca from A composite to B. Mg increased slightly from the B to C horizon (126 to 162 mg kg^{-1} respectively). K, Mg, and Ca all decreased from the A composite to E horizon and then increased from E to B horizon. The proportionate increase from E to B was small for K and Ca but especially large for Mg where there was 156 mg kg^{-1} in the A composite horizon, 48 mg kg^{-1} in the E horizon and 126 mg kg^{-1} in the B horizon. Extractable P was the only macronutrient that was quite low compared to the other macronutrients, and throughout the mineral horizons (A comp, A prof, B, E, C), P did not fluctuate much (12, 12, 7, 13, 18 mg kg^{-1} respectively).

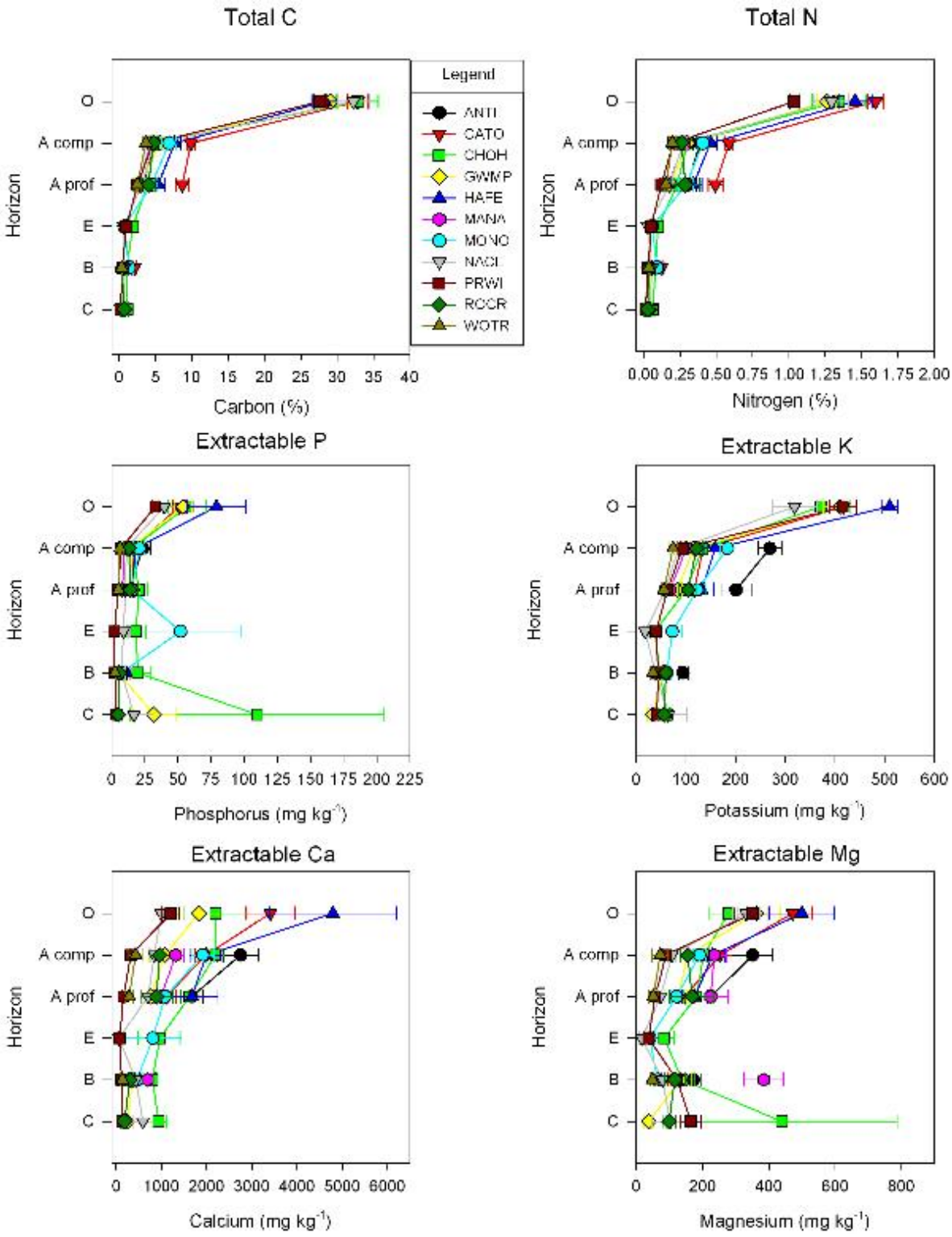

Figure 9. Distribution of total C and macronutrients (except Sulfur) by horizon in all parks of the NCRN.

Micronutrients

Micronutrients are chemical elements necessary for plant growth but in smaller quantities than the macronutrients. Micronutrients include: Cu, Fe, Mn, Zn, B, and Cl.

Throughout the NCRN parks, extractable Mn and Zn followed the same horizon-by-horizon trend as most of the macronutrients, decreasing with depth from O to C (Figure 10). Like total C, there was 3.4 and 3.3 times more Mn and Zn respectively in the O horizons compared to the A composites. Mn further decreased by a factor of 3.9 from the A composite (69 mg kg^{-1}) to the B horizon (19 mg kg^{-1}) and Zn by a factor of 2.2. Exchangeable Fe also decreased from top of the profile to the bottom, but the magnitude of the decrease was less than with Mn and Zn. The levels of Exchangeable Cu were low and fairly homogenous from top to bottom of the profile: 8.1, 4.0, 4.4, 3.7, 4.7, and 9.2 mg kg^{-1} in the O, A composite, A profile, E, B, and C horizons respectively. The higher level of extractable Cu in the C horizon is primarily attributable to one plot in PRWI with 321 mg kg^{-1} (discussed further in the PRWI Park Overview section).

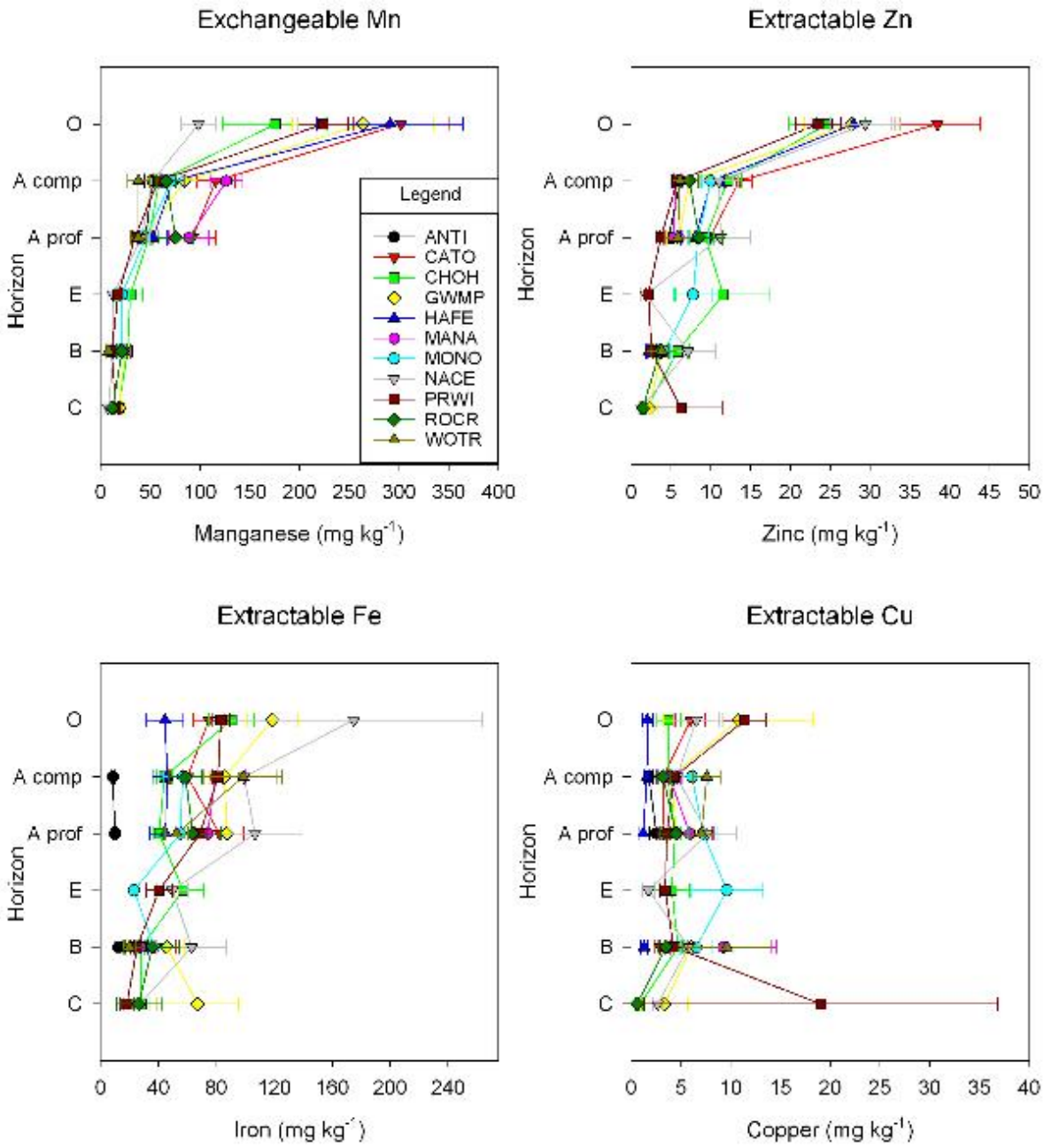

Figure 10. Distribution of micronutrients by horizon in all parks of the NCRN.

pH, CEC, base saturation

Soil pH measures the negative logarithm of the hydrogen (H) ion activity. It is considered a master soil variable because it controls so many facets of nutrient and contaminant availability and thus whether these elements are available for plant or other organism uptake. CEC measures the total of exchangeable cations (e.g., K^+, Na^+, Ca^{2+}) that a soil can absorb. Base saturation (BS) measures the percent of the CEC occupied by base (non-acid) cations: Ca, Mg, K, and Na. Since most cations are also plant nutrients, generally higher CEC and BS values indicate higher fertility and sometimes BS is used as a proxy for soil fertility.

pH varied widely among parks. PRWI had the lowest pH values of any park from the A composite to C horizon (Figure 11) ranging from 4.1 to 4.3. WOTR also had consistently low pH values throughout the profile. On the opposite end of the spectrum, ANTI and HAFE had pH values ≥ 5.8 from A composite to B horizons. In all parks except PRWI, the O horizon was more acidic than the A. At NACE the change was dramatic: an increase from an O horizon pH of 3.2 to an A horizon pH of 5.4. On average, however, the O horizon was 0.7 units more acidic than the A composite horizon below it. In addition to the among-park variation, there was also substantial variation among horizons within some parks. For example, the pH values for the O, A composite, A profile, E, B, and C horizons at NACE were 3.2, 5.4, 6.0, 4.0, 6.1, and 5.6 respectively. The pH values at MONO by horizon from O to C were 4.4, 5.2, 5.3, 6.1, 5.0, and 4.0.

Base saturation closely mirrored pH. PRWI had the lowest base saturation from the A composite to C horizon. WOTR, ROCR, and NACE also had relatively low base saturations. ANTI had the highest base saturation, and CHOH and MANA also had relatively high base saturations (>60%) from the A composite to C horizon.

CEC followed a pattern similar to total C and most of the macronutrients from the surface to base of the profile. Averaged across all parks, CEC in the O horizon was 4.6 times greater than CEC in the A composite horizon and decreased again by nearly half from A composite to B horizon. CATO and ANTI had the highest A composite CEC in the NCRN (22 and 20 meq $100g^{-1}$ respectively), and WOTR and PRWI had the lowest CEC (5.8 and 8.2 meq $100g^{-1}$ respectively). In the B and C horizons, there was little inter-park variation in CEC with values ranging from 6 to 12 meq $100g^{-1}$ in the B horizon and from 4 to 10 meq $100g^{-1}$ in the C horizon.

As discussed in the Methods section, CEC and base saturation measurements in this report are merely an approximation of the true value and thus underestimate true base saturation. These measurements are also not the methods used by the Natural Resources Conservation Service to classify soil series. Based upon Soil Taxonomy (Soil Survey Staff 2014b), these lower base saturation values indicate that there are fewer Ultisols in the NCRN than Web Soil Survey predicts (Web Soil Survey 2019). In the “Overview of soil classification, depths, water tables in the NCRN” section, the soil series presented throughout the region are those found on Web Soil Survey.

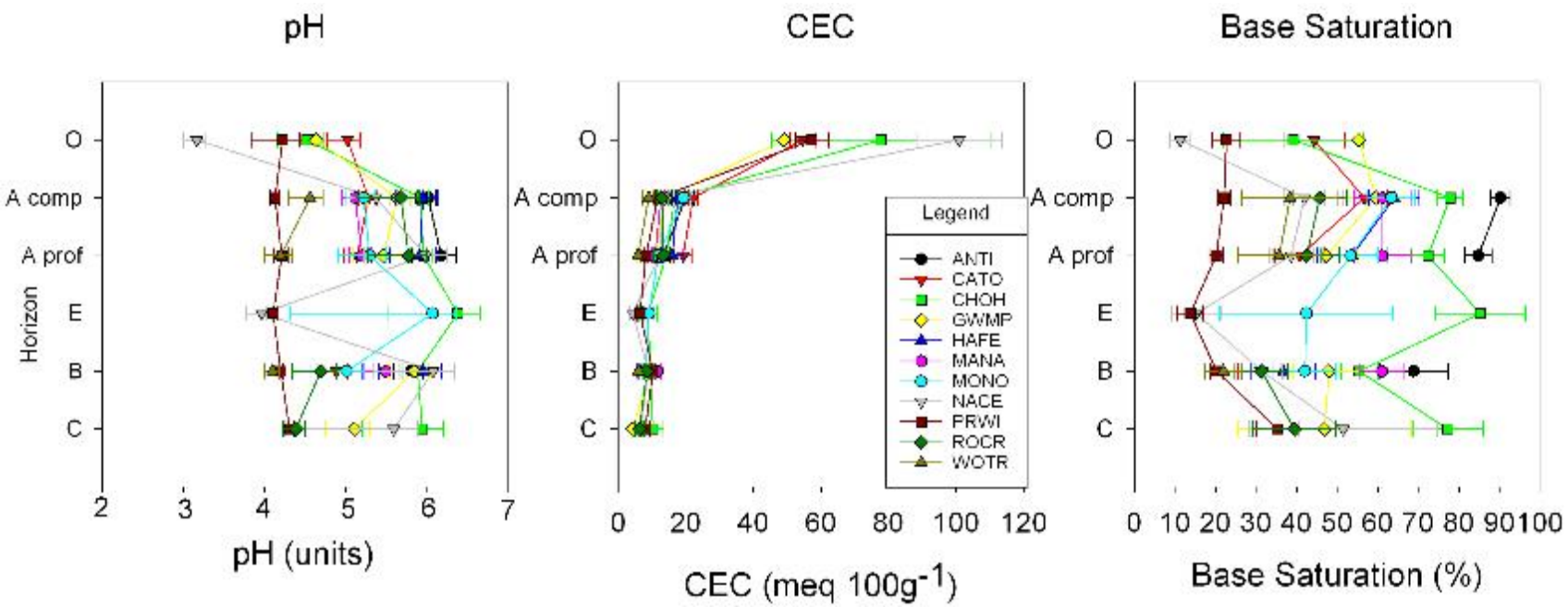

Figure 11. Distribution of pH, CEC, and Base Saturation by horizon in all parks of the NCRN.

Contaminants overview

Contaminants are operationally defined in this report as any soil elements that cause damage to plant growth or other soil organisms, or that could jeopardize human health if ingested through water or directly from soils. Contaminants are often heavy metals (e.g., Pb, Cr, Cd). Typical sources of these contaminants in the NCRN are automobile exhaust, industrial processes, and coal-fired power generation. The EPA has developed soil screening levels for these contaminants (EPA 2019) which are considered safe thresholds for residential uses and can be used for comparison with these soil data.

Soil contaminants, Cr and Cd, had low exchangeable levels throughout the region (Figure 12), though individual plots in ANTI and CHOH contained relatively higher amounts of both metals (see additional discussion in the ANTI and CHOH sections.). Many of the Cd and Cr levels in the B and C horizons were below detection limit, but in all horizons where levels were detectable the values were predominantly <1 mg kg^{-1}. NACE had 4 times more extractable Pb in its O horizon than the regional average (20 mg kg^{-1} compared to 4.8 mg kg^{-1}) and nearly 3 times more Pb in its A composite horizon (10 mg kg^{-1}) than the region (3.7 mg kg^{-1}). In addition, the three other parks nearest to Washington, D.C., and with high proportions of vehicle and human use (ROCR, WOTR, and GWMP), also had higher relative amounts of Pb in the A composite and A profile.

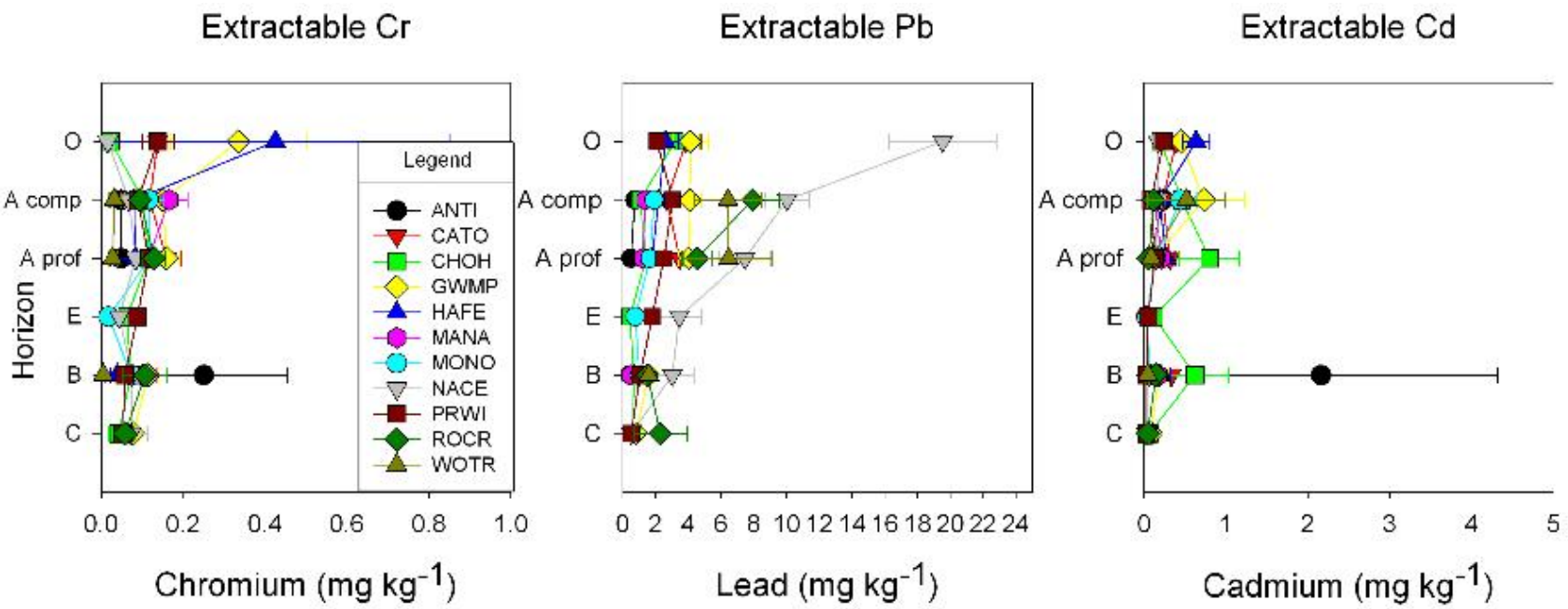

Figure 12. Distribution of contaminants by horizon in all parks of the NCRN.

Regression analysis

The regression analysis examined total C, pH, and clay percent as predictor variables for all chemical variables and showed a strong positive relationship between total C and total N (R^2 =0.91), and a positive relationship between total C and CEC (R^2 = 0.70), total C and K (R^2 =0.68), and pH and base saturation (R^2 =0.80)(Figure 13). At a pH of approximately 6.0, base saturation plateaued at 100%, and the linear relationship would have been much stronger if the samples with only a pH <6.0 were analyzed. In addition to examining all horizon samples combined, the regression analysis was performed horizon by horizon. However, this did not yield more significant relationships. Surprisingly, clay percentage was not a good predictor for any chemical variable. With its large surface area, clay typically holds a lot of charge (CEC). Frequently, clay, CEC and the abundance of macronutrients attached to the CEC are all positively related. The lack of relationship between clay and nutrients in the NCRN is undoubtedly a result of low-activity, weathered clays that do not have the charge-holding capacity of younger, high CEC clays. In addition, some of the absence of positive relationship is undoubtedly because measuring clay percentage by hand using multiple field technicians was imprecise (or too often incorrect) and masked the true effect of clay on soil chemistry in the NCRN.

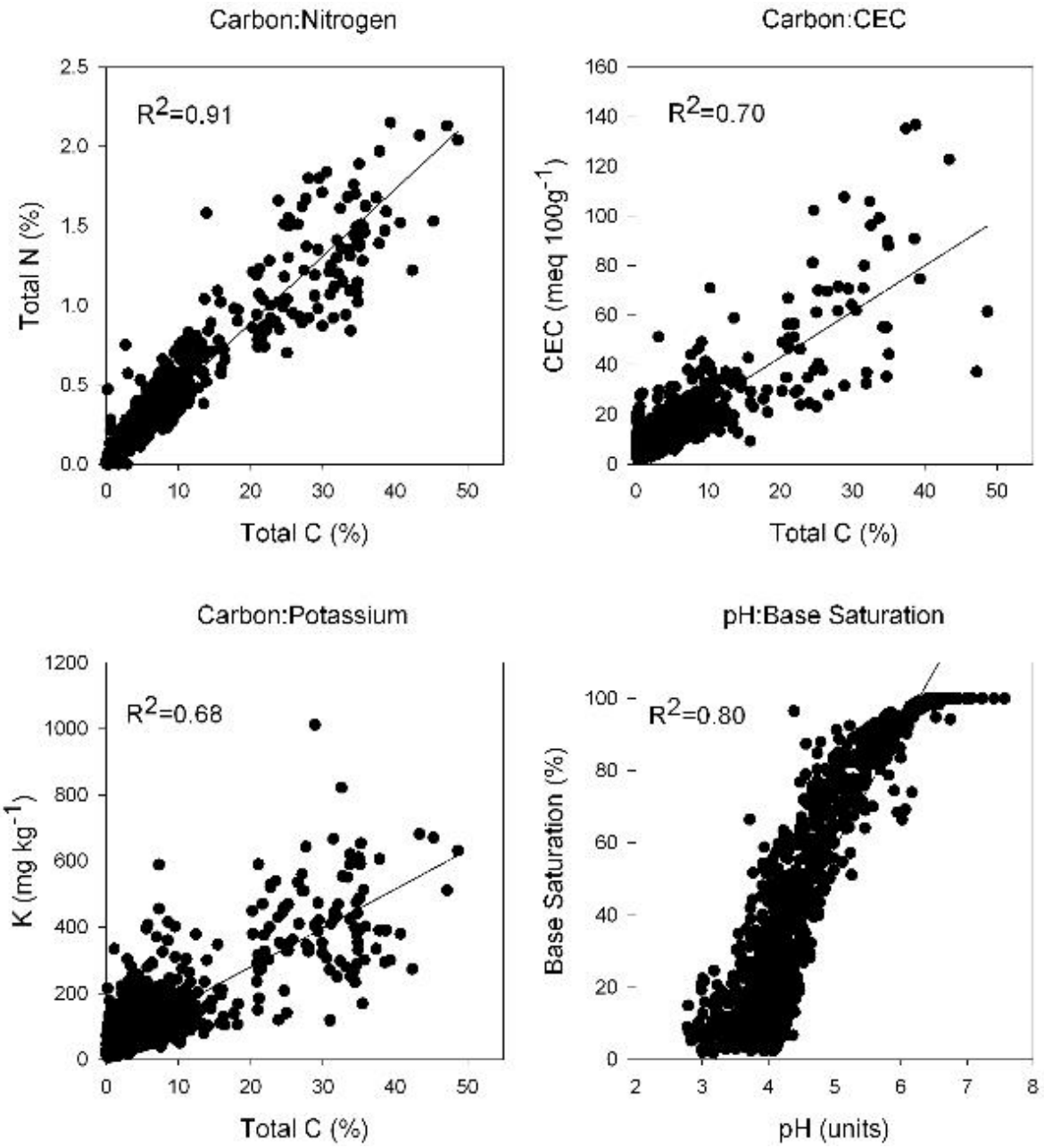

Figure 13. Regressions showing relationship between soil chemical variables in the NCRN.

Statistical differences by horizon

ANOVAs were used to detect significant differences among parks, horizon by horizon. A general pattern emerged from this analysis. A park with nutrient concentrations in the uppermost A horizon composite that were the highest or lowest in the region and statistically different from multiple other parks would often have the same highest or lowest statistically significant difference in the lower horizons. Figure 14 illustrates this pattern for total C in CATO. The A horizon composite levels in that park were statistically higher than 8 other parks in the network, and the B horizon levels were statistically higher than 5 other parks. Similarly, Figure 14 shows that PRWI had an A horizon

extractable P level that was significantly lower than 7 other NCRN parks. In the B horizon, PRWI's extractable P was still significantly lower than 6 other parks. ANTI's extractable Ca in the A horizon composite was significantly greater than extractable Ca in GWMP, NACE, and PRWI. ANTI's B horizon extractable Ca was also significantly greater than GWMP, NACE, and PRWI (Figure 14).

Appendix C gives the tables of P values that were used to find significant differences among parks for each horizon using the post hoc Dunn's multiple comparison test when the ANOVA had a P value ≤ 0.05.

For the O horizon, the ANOVA showed no significant differences between parks for K, Mg, Fe, or Cu. Total C, total N, extractable P, Ca, and Zn were all significantly higher in CATO than PRWI. HAFE contained significantly higher extractable P than PRWI and significantly higher extractable Ca than NACE and PRWI. Mn in CATO was significantly higher than NACE.

In the A composite horizon, the differences for total C, extractable P and Ca can be seen in Figure 14. Total N followed the same pattern as total C and PRWI had significantly or near significantly ($P<0.1$) lower levels than all parks except MANA, ROCR, and WOTR. ANTI's extractable K levels were significantly greater than most other parks and NACE and PRWI had significantly lower levels than most other parks.

The A horizon profile samples had similar statistical differences to the A composite horizon. The ANOVA showed no significant differences between the depth of the horizon midpoint from which all chemical samples were taken. Thus, the data indicates that the A horizon profile chemical samples were all taken from around the same depth in the profile (12 cm was the NCRN average midpoint for the A horizon.).

There was no significant difference in E horizon chemistry for extractable Mg, Mn, CEC, Fe, or Cu. clay percentage between parks. There was also no significant difference in clay content or depth of the horizon midpoint (25 cm was the NCRN average midpoint for the E horizon.).

The most variation among parks occurred in the B horizon, and all physical and chemical variables contained significant differences. CATO's B horizon midpoint was significantly shallower in the profile (36 ± 16 cm) than CHOH, MANA, NACE, and PRWI. HAFE's midpoint (35 ± 15 cm) was significantly shallower than CHOH, NACE, and PRWI. All other horizons parks were not statistically different. For the rest of the chemical and physical differences, see Appendix C.

Extractable P, K, Mg, Mn, and Zn in the C horizon were not significantly different in the NCRN plots. Horizon midpoints were also not statistically significant, though GWMP was nearly significantly ($P<0.1$) shallower in the profile (54 cm depth) than PRWI (84 cm depth). For all other significance levels see Appendix C.

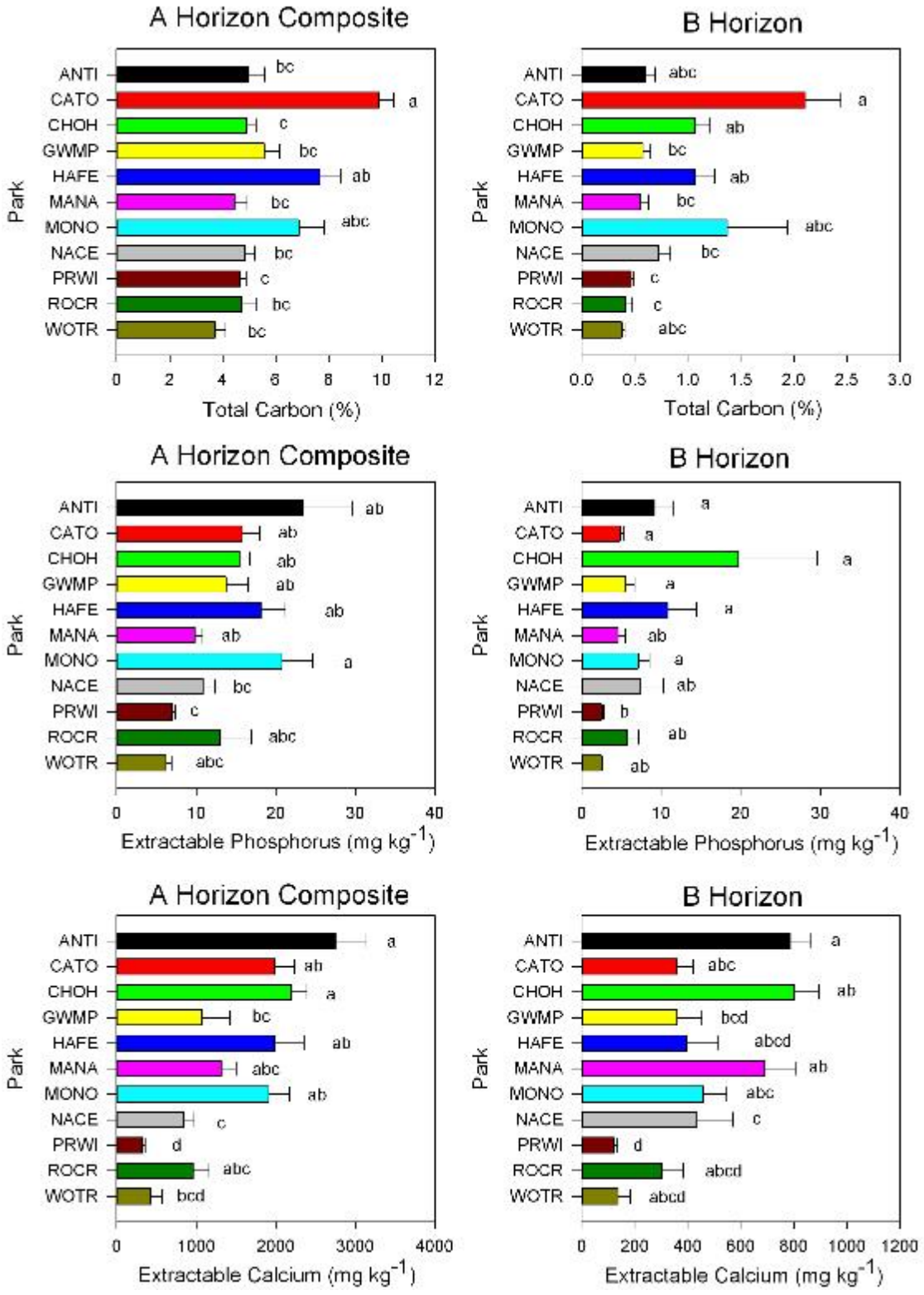

Figure 14. Total C, extractable P and K levels in the A composite and B horizons of the NCRN. Parks with values that are significantly different do not share the same letter next to their bar.

Overview of soil classification, depths, and water tables in the NCRN

There are 85 total soil series represented in the NCRN parks (Table 2) according to Web Soil Survey (Web Soil Survey 2019). A soil series is the most specific unit of soil taxonomy, akin to a species in the plant and animal kingdoms (Soil Survey Staff 2014b) (discussed further in Appendices A and D). Some series are well represented in multiple parks, whereas others are found in only one park. Approximately one quarter of the NCRN's soils are shallow (<50 cm deep), one quarter are moderately deep (50–100 cm deep), and one half are at least 100 cm deep based on the depth that samplers were able to auger before hitting bedrock or an impenetrable zone. (In this survey, fragipans and other restrictive layers were inconsistently identified by field technicians, but based on descriptive evidence as well as NRCS soil mapping, some of the shallow soils can be attributed to fragipans.) Two thirds of plots contained a Bt horizon—a horizon with a heavy accumulation of illuviated clay indicating well weathered, old soils that belong to the Ultisols or Alfisols soil order (see definition in Appendix A), and another 21% of soils contained a Bw horizon most often associated with profiles that have had insufficient time or improper climate conditions (e.g., too cold and insufficient rain) to form a Bt horizon. A little over a quarter of the region's soils have an O horizon (an organic layer covering the soil surface), which are frequently associated with forest soils (see Discussion). Finally, 17% of the region's soils were poorly or somewhat poorly drained, indicating that they experience saturated soil conditions (all soil pores are filled with water) in the top 100cm of soil for *at least* three to four weeks of the year, during periods of high microbial activity (e.g., in the warm months of spring and summer). This means that the high-water table could be within 100 cm of the soil surface all winter and also for three to four weeks in the spring. Poorly drained soils have a water table within the top 50 cm of the soil surface and somewhat poorly drained within 50 to 100 cm of the soil surface.

Table 2. Assorted soil profile characteristics from parks in the NCRN.

Park	Number of Profiles	Number of Soil Series	Profiles 0–50 cm deep	Profiles 50–100 cm deep	Profiles ≥ 100 cm deep	Profiles w/ O horizons	Profiles w/ Bt horizons	Profiles w/ Bw horizons	Poorly or somewhat poorly drained soils
ANTI	13	5	1	7	5	1	11	1	0
CATO	46	10	28	14	4	16	25	9	1
CHOH	67	30	20	15	30	4	31	25	6
GWMP	28	11	4	8	16	4	19	6	6
HAFE	21	10	14	5	2	5	6	8	1
MANA	19	6	1	7	10	2	13	5	11
MONO	15	6	9	4	3	0	4	4	1
NACE	47	18	7	13	28	14	37	10	16

* NOTE there are 85 distinct soil series in the NCRN. However, 33 soil series are seen in multiple parks. If those that were counted in multiple parks were summed, the result would be 118 soil series.

Table 2 (continued). Assorted soil profile characteristics from parks in the NCRN.

Park	Number of Profiles	Number of Soil Series	Profiles 0–50 cm deep	Profiles 50–100 cm deep	Profiles ≥ 100 cm deep	Profiles w/ O horizons	Profiles w/ Bt horizons	Profiles w/ Bw horizons	Poorly or somewhat poorly drained soils
PRWI	145	16	19	40	88	64	121	15	25
ROCR	19	4	1	4	14	3	9	4	3
WOTR	6	2	2	3	1	1	4	0	0
Total	426	85*	106	120	201	114	280	87	70

* NOTE there are 85 distinct soil series in the NCRN. However, 33 soil series are seen in multiple parks. If those that were counted in multiple parks were summed, the result would be 118 soil series.

Park Overviews

Antietam National Battlefield

ANTI is located in the Hagerstown Valley, part of the Great Appalachian Valley of the Ridge and Valley physiographic province in Washington County, Maryland. The geology of the Hagerstown Valley is predominantly carbonate rocks, and Antietam Creek, a tributary of the Potomac River, runs through the park.

There are thirteen long-term vegetation monitoring plots in ANTI (Table 3). The soils of these plots uniformly belonged to the Alfisols soil order. These are soils that have a high percentage of clay in the B horizon and are typically quite fertile containing higher amounts of cations, which are useful for plant growth. Five soil series are present in ANTI's plots: Carbo, Duffield, Hagerstown, Ryder, and Swanpond. Hagerstown was the most prevalent series in the park found in five plots, and Duffield was the series in three plots. (For a list of all soil series in the NCRN, their parent materials, and landscape positions see Appendix D.)

A unique characteristic of ANTI soils is that they were all formed from the same parent material—residual limestone rocks. All other parks in the region contained at least two different parent materials and rock types. As a result limestone parent material, pH and base saturation levels in ANTI were consistently high throughout the profile with averages ≥ 5.7 and 69 respectively (Table 3). The pH and base saturation values in ANTI were either the highest or among the highest of any park in the region.

Extractable Ca and Mg levels in the A composite horizon were higher than any other park of the NCRN, and in the B horizon they were the second highest levels. This is attributable to the $CaCO_3$ and $MgCO_3$ comprising the limestone parent material. The parent material also affected K levels, which were significantly higher than most other parks in the region. Interestingly, extractable Fe was significantly lower than all other parks in the region except HAFE (another park in the Ridge and Valley Province). Soil pH exerts a strong influence on extractable Fe levels. At high pH values, Fe is not as available for plant uptake which is why blueberries (which require high amounts of Fe) grow

better in acidic soils. It follows, therefore, that ANTI soils with a higher pH would also have low levels of extractable Fe.

One plot, ANTI-0200, had outlier high values of extractable Cd (28 mg kg^{-1}) and Cr (3 mg kg^{-1}) in the B horizon. For context, the plot with the next highest level of Cd had 0.06 mg kg^{-1}. pH in the B horizon (which has a controlling effect on Cd and Cr) was 3.98 which suggests that a localized change in parent material might be responsible for the extremely high values. Moreover, the technicians were not able to dig below 68 cm which also indicates that perhaps a change of parent material at the base of the horizon caused the high Cd and Cr. However, the A profile horizon pH was 5.77, nearly 100 times greater than in the B horizon which also could indicate that there is some form of metal object (perhaps of historical or archaeological interest) buried in the soil that is causing the low pH and high levels of extractable Cd and Cr. We suggest further inquiry.

Clay values were some of the highest in the region which is typical of limestone residual soils in the Hagerstown Valley. However, only five of the twelve plots were able to be excavated down to 100 cm, which suggests shallow soils across the park. There were no E or C horizons in any plots. The absence of E horizons is due to high clay and non-acid (base cations) levels in the soil. The lack of C horizons indicates an abrupt change from clay to limestone bedrock and little transitional weathering of that bedrock.

Table 3. Soil physical and chemical characteristics ± standard deviation by horizon in ANTI.

Soil Variables	O horizon‡‡	A horizon composite	A horizon profile	B horizon
n	1	12	9	13
Horizon midpoint	n.a.	n.a.	11 ± 6	49 ± 12
Clay	n.a.	n.a.	17 ± 7	32 ± 15
Coarse fragments	n.a.	n.a.	7 ± 11	23 ± 31
pH	5.7	6.0	6.2	5.8
CEC	20 ± n.a.	20 ± 8.7	13 ± 5.1	9.4 ± 4.7
BS	94 ± n.a.	90 ± 7.5	85 ± 8.8	69 ± 27
Total C	n.a.	5.0 ± 2.2	3.3 ± 1.6	0.6 ± 0.3
Total N	n.a.	0.39 ± 0.17	0.30 ± 0.16	0.07 ± 0.05
P	37 ± n.a.	23 ± 21	13 ± 8.8	9.2 ± 8.5
K	500 ± n.a.	270 ± 82	200 ± 92	94 ± 32
Ca	2670 ± n.a.	2750 ± 1340	1670 ± 737	787 ± 275

‡‡ If horizons are not shown in a table (i.e., no E or C horizon in this table), it signifies that those horizons were not present throughout the park.

§ b.d.l. stands for below detection limit.

Table 3 (continued). Soil physical and chemical characteristics ± standard deviation by horizon in ANTI.

Soil Variables	O horizon‡‡	A horizon composite	A horizon profile	B horizon
Mg	450 ± n.a.	350 ± 210	230 ± 160	170 ± 75
Na	35 ± n.a.	13 ± 7.3	10 ± 1.8	11 ± 6.2
Mn	80 ± n.a.	52 ± 26	45 ± 18	16 ± 13
Fe	22 ± n.a.	8.5 ± 4.7	10 ± 3.1	12 ± 6.5
Cu	12 ± n.a.	1.8 ± 1.4	2.5 ± 2.1	3.9 ± 3.1
Zn	21 ± n.a.	6.2 ± 3.7	4.7 ± 3.5	2.7 ± 2.6
Ni	2 ± n.a.	0.8 ± 0.2	0.8 ± 0.3	0.8 ± 0.5
Mo	b.d.l.§	0.03 ± 0.06	0.02 ± 0.05	0.1 ± 0.3
Pb	2.5 ± n.a.	0.7 ± 0.4	0.5 ± 0.4	0.5 ± 0.5
Cd	b.d.l.	0.24 ± 0.47	0.07 ± 0.06	2.2 ± 7.5
Cr	b.d.l.	0.05 ± 0.08	0.05 ± 0.08	0.3 ± 0.7

‡‡ If horizons are not shown in a table (i.e., no E or C horizon in this table), it signifies that those horizons were not present throughout the park.

§ b.d.l. stands for below detection limit.

Catoctin Mountain Park

CATO is the only park in the NCRN entirely within the Blue Ridge physiographic region. The soils in this park are all located either on a mountain summit or side slope (many of them with a high percentage grade). In total, 46 long-term vegetation monitoring plots in CATO were sampled for soil. Ten soil series are found in those plots: Airmont, Bagtown, Edgemont, Highfield, Myersville, Ravenrock, Rohrersville, Stumptown, Thurmont, and Zion. Ravenrock is the predominant series in CATO, located in ten plots, and Highfield was the primary series in seven plots. Bagtown, Stumptown, Thurmont, and Zion were all found in only one plot.

CATO's soils are mostly shallow to very shallow over bedrock. For two thirds of the plots (25 total), the field technicians could only excavate to 50 cm below the surface. Moreover, only four plots have profile descriptions to a depth of 100 cm. The shallow soils are due to a number of factors, chief among them the underlying geology of very hard metamorphic and some igneous rocks. The climate is also cooler than other areas of the Mid-Atlantic (primarily due to elevation), and weathering occurs more slowly. Because of the steep mountain slopes, the soils of CATO are naturally prone to erosion.

The two major classes of parent materials in the park are colluvium (parent materials that have moved downslope by gravity) and residuum. The rocks which the soils formed from are primarily metarhyolite, schist, metabasalt, greenstone, and quartz phyllite. Boulders are evident throughout the park on the surface of the soil.

Eighty-two percent of the soils in CATO belong to the Alfisol soil order and the other eighteen percent to the Ultisols, which are more weathered than alfisols and have a lower percentage of base cations and typically a lower pH. Though CATO's soils were shallow, 68% of its plots contained an O horizon, making it the park with the highest percentage of plots with O horizons in the NCRN. PRWI was second highest, but only 28% of its plots had an O horizon. There were no delineated E horizons in CATO, and only one C horizon.

Physical characteristics showed that the soils of CATO are in good health, providing important ecosystem services—water infiltration, storage and filtration, a porous medium excellent for root growth, and a habitat for soil fauna. D_b was lower in CATO than all other parks in the region, and infiltration was the most rapid. The average porosity of a CATO soil (the percentage of pore space in the soil matrix) was very high due to the very high levels of soil C. (Because soil C was so high a particle density $\{D_p\}$ of 2.65 g cm^{-3} could not be assumed and thus used to calculate porosity, however, infiltration rates suggest abundant macropores.) Penetration resistance was quite low compared to other parks in the region.

The chemical variables in the park (Table 4) were also some of the highest in the region (typically in the top third of parks in the NCRN). Total C and Total N were the highest among other parks in the surface mineral horizons, and the other extractable macro and micronutrients (except for Fe and Cu) were also high. Contaminants were very low compared to EPA screening levels.

Table 4. Soil physical and chemical characteristics in CATO.

Soil Variables	O horizon	A horizon composite	A horizon profile	B horizon	C horizon
n	26	37	30	31	1
Horizon midpoint	3.8 ± 2.7	n.a.	10 ± 6	36 ± 16	38 ± n.a.
Clay	n.a.	n.a.	14 ± 4	30 ± 20	26 ± n.a.
Coarse fragments	n.a.	n.a.	24 ± 23	23 ± 7.3	85 ± n.a.
pH	5.0	5.3	5.1	4.9	4.4 ± n.a.
CEC	55 ± 14	22 ± 7.8	19 ± 13	9.0 ± 3.3	6 ± n.a.
BS	44 ± 29	57 ± 30	41 ± 31	31 ± 27	17 ± n.a.
Total C	33 ± 7.1	9.9 ± 3.4	8.7 ± 5.0	2.1 ± 1.8	1.4 ± n.a.
Total N	1.6 ± 0.29	0.59 ± 0.18	0.50 ± 0.27	0.12 ± 0.09	0.09 ± n.a.
P	51 ± 24	16 ± 13	17 ± 18	4.8 ± 2.7	5.1 ± n.a.
K	420 ± 140	130 ± 51	120 ± 75	49 ± 23	40 ± n.a.
Ca	3410 ± 2760	1990 ± 1510	1100 ± 1210	361 ± 330	138 ± n.a.
Mg	470 ± 300	250 ± 220	150 ± 150	82 ± 78	20 ± n.a.

Table 4 (continued). Soil physical and chemical characteristics in CATO.

Soil Variables	O horizon	A horizon composite	A horizon profile	B horizon	C horizon
Na	83 ± 69	30 ± 28	25 ± 23	22 ± 22	8.8 ± n.a.
Mn	300 ± 240	120 ± 120	92 ± 130	26 ± 19	18 ± n.a.
Fe	75 ± 55	60 ± 70	82 ± 91	44 ± 40	13 ± n.a.
Cu	6.0 ± 7.4	3.2 ± 3.4	3.3 ± 3.5	2.9 ± 2.6	3.8 ± n.a.
Zn	38 ± 28	14 ± 9.7	9.9 ± 8.5	3.2 ± 2.9	2.8 ± n.a.
Ni	2.6 ± 1.2	1.8 ± 0.78	1.6 ± 0.88	1.6 ± 2.0	0.5 ± n.a.
Mo	0.1 ± 0.1	0.2 ± 0.4	0.2 ± 0.5	0.1 ± 0.2	b.d.l.
Pb	3.9 ± 4.7	2.7 ± 3.6	3.5 ± 3.9	1.0 ± 1.5	0.34 ± n.a.
Cd	0.4 ± 0.4	0.2 ± 0.09	0.3 ± 0.3	0.3 ± 1.4	0.03 ± n.a.
Cr	0.1 ± 0.2	0.1 ± 0.2	0.2 ± 0.2	0.1 ± 0.1	0.02 ± n.a.

Chesapeake and Ohio National Historic Park

The Chesapeake and Ohio canal begins in Washington, D.C. and parallels the Potomac river west and north for approximately 180 miles. It is the only park in the region that spans all four physiographic provinces. Consequently, the soils in this park are quite diverse. There are 30 soil series in CHOH, scattered across 67 permanent vegetation monitoring plots: Airmont, Allegheny, Atkins, Beltsville, Berks, Bigpool, Blocktown, Bownmansville, Brinklow, Codorus, Combs, Downsville, Elk, Funkstown, Gilpin, Glenelg, Hagerstown, Hatboro, Hazel, Huntington, Lindside, Melvin, Monogahela, Nollville, Opequon, Penn, Pope, Ryder, Swanpond, Talladega, and Trego (see Appendix D for descriptions of the series). Sixteen of the 30 soil series are found in only one plot. Lindside and Downsville were the most ubiquitous soils in the region and comprised the dominant series at CHOH, found in eight and six plots respectively.

Most of the CHOH plots are located either on the historical Potomac River floodplain or an ancient stream terrace from the days when the river was much wider. Other plots are periodically flooded by rising waters in the canal itself. As a result, CHOH is the NCRN's park with the highest proportion of plots with younger soils in the Inceptisol order (38% of plots), which contain weakly developed Bw horizons. These horizons have not had enough time for clay to move down from the surface and settle in the Bt horizon, generating the increase in clay with depth and the pronounced structure found in Alfisols and Ultisols. CHOH is also the only park in the region with soils in the order Mollisols (6 plots total) which have thick, dark A horizons and a high amount of organic C and base saturation. These soils can be found where flooding and saturated conditions simultaneously introduce and prevent the decomposition of organic material. The rest of the soils in CHOH were Alfisols (23%) or Ultisols (29%).

Predictably, the parent materials in the park were also quite diverse. Alluvium (parent materials deposited by rivers or moving water) comprised 58% of the plots. The rest of the plots had an

assortment of colluvium, residuum, and two plots within or close to Washington D.C. possibly contained old coastal plain sediments. The mineral fraction of the parent materials was composed of both acidic and basic (carbonate) rocks. Shale, siltstone, sandstone, schist, quartzite, and limestone were the primary rocks in the parent material. Nearly 10% of plots would be classified as poorly or somewhat poorly drained (meaning they contained saturated soil conditions for at least a few consecutive weeks of the growing season in the upper 50 cm of the soil profile).

The soil physical conditions were close to the average for the region. The clay percentages were in the middle of the parks. However, infiltration rates were in the top third for the NCRN.

Soil chemical values (Table 5) showed that the soils of CHOH were quite fertile. CEC and Base saturation values were some of the highest in the region. This is almost certainly due to the sediment deposition from Potomac River flooding events which replenish the surface of the soil with nutrients. Total C and extractable P, Ca, and Mg were also very high.

Plot CHOH-0262 was an outlier for extractable P, containing 299, 546, and 397 mg kg^{-1} in the A, B, C horizons respectively (the B horizon P average for CHOH was 20 mg kg^{-1}). Extractable Mg was also extremely high in CHOH-0262 ranging from 1480 to 2080 mg kg^{-1} through the profile. The high levels throughout the profile suggest that there was a smelter on the site or perhaps something that produced a heavy amount of wood ash or manure. CHOH-1350 also had unusually high extractable P values (162 and 172 mg kg^{-1}) in the A and B horizons respectively. CHOH-0380 contained 16.2 mg kg extractable Cd in the A horizon and 23.0 mg kg^{-1} in the B horizon which suggests that there was some form of human activity on the site that contributed to these outlier values throughout the profile. Likewise CHOH-0026 contained 7.9 mg kg^{-1} Cd in the A horizon and 7.0 mg kg^{-1} in the B horizon. Both CHOH-0380 and CHOH-0026 contain different soil series which further supports the hypothesis that the high Cd levels are caused by human activity. We suggest further inquiry into the history of all of these outlier plots.

Table 5. Soil physical and chemical characteristics in CHOH.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	7	65	50	4	57	4
Horizon midpoint	n.a.	n.a.	15 ± 12	24 ± 6.7	50 ± 20	50 ± 37
Clay	n.a.	n.a.	17 ± 7	12 ± 6.5	25 ± 10	9.8 ± 5.9
Coarse fragments	n.a.	n.a.	8 ± 12	22 ± 34	10 ± 18	21 ± 14
pH	4.5	5.9	6.0	6.4	5.9	5.9
CEC	78 ± 56	17 ± 8.6	14 ± 8.7	8.8 ± 3.9	9.4 ± 3.9	10 ± 5.4
BS	39 ± 30	78 ± 23	72 ± 26	85 ± 16	55 ± 31	77 ± 15
Total C	33 ± 7.7	4.9 ± 2.9	3.9 ± 3.4	1.9 ± 0.6	1.1 ± 1.1	1.1 ± 0.4
Total N	1.3 ± 0.5	0.30 ± 0.12	0.23 ± 0.14	0.1 ± 0.05	0.08 ± 0.05	0.1 ± 0.02
P	57 ± 38	15 ± 11	20 ± 46	18 ± 13	20 ± 74	110 ± 170
K	370 ± 160	130 ± 88	100 ± 54	37 ± 16	47 ± 26	63 ± 11
Ca	2200 ± 1820	2190 ± 1580	1630 ± 1490	963 ± 824	803 ± 699	940 ± 277
Mg	280 ± 150	200 ± 150	180 ± 280	85 ± 53	140 ± 270	440 ± 600
Na	84 ± 72	22 ± 20	21 ± 21	18 ± 7.4	21 ± 26	19 ± 5.1
Mn	180 ± 140	59 ± 32	49 ± 28	30 ± 21	27 ± 22	18 ± 7.0
Fe	91 ± 41	44 ± 44	41 ± 26	57 ± 24	28 ± 17	28 ± 8.8
Cu	3.8 ± 3.1	3.8 ± 3.5	4.4 ± 4.3	4.1 ± 3.1	4.7 ± 5.1	0.9 ± 0.5
Zn	25 ± 13	12 ± 15	9.3 ± 7.0	12 ± 10	5.8 ± 11	2.0 ± 1.2
Ni	2.4 ± 0.6	2.0 ± 1.3	2.2 ± 1.8	3.6 ± 2.9	2.0 ± 1.5	2.5 ± 1.5
Mo	0.1 ± 0.4	0.05 ± 0.09	0.07 ± 0.2	b.d.l.	0.1 ± 0.2	0.1 ± 0.04
Pb	3.2 ± 3.9	1.1 ± 1.3	1.4 ± 2.9	0.5 ± 0.3	0.7 ± 0.8	0.6 ± 0.05
Cd	0.2 ± 0.1	0.5 ± 2	0.8 ± 3	0.1 ± 0.1	0.6 ± 3.1	0.07 ± 0.04
Cr	0.02 ± 0.06	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.04 ± 0.04

George Washington Memorial Parkway

The GWMP follows the Virginia side of the Potomac River from George Washington's home, Mount Vernon, to Great Falls Park, north of the I-495 Capital Beltway (a distance of approximately 30 miles). The parkway crosses both the eastern edge of the Piedmont Plateau and the western edge of the Coastal Plain, though >70% of its 28 long-term vegetation monitoring plots are in the Piedmont Region. There are 11 soils series in GWMP: Baile, Blocktown, Brinklow, Elkton, Fluvaquents, Glenelg, Hatboro, Mattapex, Meadowville, Rhodhiss, and Sassafras. Glenelg was the most prevalent series in the park found in 11 (39%) of the plots.

Many of the plots in GWMP are close to the Potomac River, but unlike CHOH, the soils in only 5 plots (18% of the total) were formed from alluvial parent materials. This is due to the fact that tall bluffs rise steeply from the Virginia side of the river, in the section from D.C. to the Beltway. Many of the vegetation monitoring plots are located on the summit or slopes of those bluffs. Consequently, a majority of soils in the GWMP are formed from metamorphic residual rocks, predominantly schist, quartzite, and phyllite. Four of the plots on the Coastal Plain are underlain by ancient marine sediments.

Eighty nine percent of the soils in GWMP are Ultisols. Two plots have Inceptisols, and one plot has a soil that classifies as an Entisols making it one of only two parks with this soil order (NACE also has two plots with Entisols).

There were no physical or chemical outliers in GWMP soils (Table 6). It was a park with few statistically significant differences from the other parks in the NCRN. This suggests two things: first, that GWMP's soils are fairly uniform (e.g., 89% are Ultisols formed from the same type of parent material and having a similar landscape position.) and second, that the soils in GWMP could be considered the central concept of an NCRN soil, or soils that most "typify" the region.

Table 6. Soil physical and chemical characteristics in GWMP.

Soil Variables	O horizon	A horizon composite	A horizon profile	B horizon	C horizon
n	7	28	20	23	4
Horizon midpoint	2 ± n.a.	n.a.	12 ± 7	52 ± 14	54 ± 15
Clay	n.a.	n.a.	16 ± 7	24 ± 9.6	9.0 ± 4.1
Coarse fragments	n.a.	n.a.	3 ± 5	7 ± 13	34 ± 36
pH	n.a.	5.6	5.5	6.1	5.1
CEC	n.a.	14 ± 10	11 ± 4.3	9.3 ± 3.3	4.2 ± 1.0
BS	n.a.	60 ± 29	47 ± 34	48 ± 34	47 ± 37
Total C	29 ± 6.7	5.6 ± 3.0	2.9 ± 1.1	0.6 ± 0.3	0.5 ± 0.2
Total N	1.3 ± 0.17	0.30 ± 0.12	0.18 ± 0.087	0.05 ± 0.02	0.04 ± 0.02
P	54 ± 18	14 ± 15	16 ± 25	5.6 ± 4.9	32 ± 28
K	410 ± 87	120 ± 49	82 ± 40	54 ± 22	33 ± 17
Ca	1830 ± 1210	1070 ± 1850	765 ± 899	361 ± 442	245 ± 200
Mg	360 ± 190	160 ± 120	130 ± 114	130 ± 150	38 ± 24

Table 6 (continued). Soil physical and chemical characteristics in GWMP.

Soil Variables	O horizon	A horizon composite	A horizon profile	B horizon	C horizon
Na	95 ± 110	30 ± 23	23 ± 15	33 ± 44	13 ± 3.9
Mn	260 ± 190	84 ± 71	45 ± 29	24 ± 19	18 ± 13
Fe	120 ± 47	86 ± 61	87 ± 81	46 ± 58	67 ± 49
Cu	11 ± 20	4.0 ± 5.2	4.6 ± 7.9	6.1 ± 9.5	3.4 ± 4.1
Zn	28 ± 16	7.4 ± 6.2	6.0 ± 6.7	3.8 ± 4.3	2.3 ± 1.8
Ni	4.2 ± 0.52	1.8 ± 0.78	1.5 ± 0.91	1.7 ± 1.1	3.2 ± 2.7
Mo	0.3 ± 0.4	0.1 ± 0.2	0.1 ± 0.2	0.1 ± 0.1	0.1 ± 0.1
Pb	4.1 ± 2.8	4.1 ± 3.6	4.0 ± 2.9	1.6 ± 2.1	0.8 ± 0.5
Cd	0.5 ± 0.7	0.7 ± 3	0.1 ± 0.1	0.2 ± 0.5	0.1 ± 0.1
Cr	0.3 ± 0.4	0.2 ± 0.2	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1

Harpers Ferry National Historical Park

HAFE sits at the confluence of the Shenandoah and Potomac Rivers and the intersection of the Blue Ridge and Ridge and Valley physiographic provinces. Its 21 long-term vegetation monitoring plots are mostly scattered on the mountains surrounding the historic town, though at least one is on the Potomac River floodplain.

The majority of plots are underlain by residual and colluvial metamorphosed slate, phyllite, schist, quartzite, and greenstone. However, 4 of its plots sit atop sedimentary sandstone, and one consists of limestone residuum.

Roughly two thirds of the plots are characterized by the soil order Ultisols and the other one third are Inceptisols. Ten soil series are present in HAFE's plots: Airmont, Bagtown, Catoctin, Dekalb, Hazel, Lindside, Purcellville, Stumptown, Weverton, and Whiteford. Bagtown was the most prevalent (5 plots), and Whiteford was the second most prevalent (4 plots).

Soil physical and chemical characteristics of HAFE (Table 7) were similar to those of CATO. This is not surprising, given the two parks share similar soil series. The soil profiles in HAFE were some of the shallowest in the NCRN. A profile deeper than 50 cm could only be excavated in one third (7) of the plots, and a 100 cm deep profile was only achievable in 2 plots. From profile surface to base, HAFE had the lowest clay percent of any park in the NCRN. Like CATO, it was characterized by a high coarse fragment percentage. HAFE's D_b values were the second lowest in the region behind CATO, and its total C values in the mineral surface (A) horizons were the second highest in the region behind CATO. Total N in HAFE and CATO were either the highest or second highest of all parks.

pH levels were all ≥ 5.9 (among the highest in the region). Most of the other extractable macronutrients were very high in HAFE's soils (in the top third of values for the NCRN parks) probably because they have not had enough time to weather out of the soil. The level of extractable micronutrients, Mn and Zn, were similarly high. The nutrient data indicates that the soils are in very good health and able to support vigorous plant growth. However, like CATO, the levels of Fe and Cu were some of the lowest in the region. As discussed with ANTI, the high pH levels probably limited the extractable Fe present in HAFE soils. Extractable Cd and Cr levels in the O horizon were higher than in any other park, but the absolute values of those contaminants was still <1 mg kg^{-1}.

Table 7. Soil physical and chemical characteristics in HAFE.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon
n	4	21	18	3	17
Horizon midpoint	n.a.	n.a.	9 ± 5	18 ± 7.2	35 ± 15
Clay	n.a.	n.a.	11 ± 4	12 ± 4.2	16 ± 8.3
Coarse fragments	n.a.	n.a.	18 ± 15	38 ± 27	25 ± 18
pH	n.a.	6.0	5.9	6.8	6.0
CEC	n.a.	18 ± 7.4	16 ± 14	8.9 ± 5.1	6.4 ± 2.7
BS	n.a.	64 ± 24	54 ± 34	52 ± 36	37 ± 31
Total C	28 ± 3.6	7.7 ± 3.5	5.4 ± 3.7	1.4 ± 0.2	1.1 ± 0.7
Total N	1.5 ± 0.23	0.46 ± 0.21	0.34 ± 0.25	0.1 ± 0.01	0.07 ± 0.05
P	79 ± 44	18 ± 14	15 ± 18	23 ± 25	11 ± 14
K	510 ± 33	160 ± 92	130 ± 100	28 ± 12	57 ± 41
Ca	4790 ± 2800	1990 ± 1670	1680 ± 2470	1140 ± 1310	396 ± 482
Mg	500 ± 200	230 ± 170	180 ± 160	120 ± 100	64 ± 52
Na	45 ± 7.8	16 ± 6.3	17 ± 10	8.4 ± 2.8	14 ± 7.7
Mn	290 ± 150	72 ± 51	53 ± 58	17 ± 7.5	16 ± 16
Fe	45 ± 26	46 ± 48	45 ± 46	24 ± 5.7	28 ± 19
Cu	1.6 ± 1.0	1.6 ± 1.1	1.2 ± 1.5	1.7 ± 1.0	1.3 ± 1.4
Zn	28 ± 9.2	10 ± 7.0	8.0 ± 7.5	5.5 ± 3.2	2.2 ± 1.4
Ni	2.4 ± 1.2	1 ± 0.3	1 ± 0.6	0.6 ± 0.2	1.7 ± 1.8
Mo	0.3 ± 0.5	0.06 ± 0.2	0.06 ± 0.2	b.d.l.	0.04 ± 0.1
Pb	2.6 ± 1.6	2 ± 2	1.8 ± 1.5	0.6 ± 0.3	0.7 ± 0.4
Cd	0.6 ± 0.3	0.2 ± 0.2	0.3 ± 0.4	0.1 ± 0.03	0.2 ± 0.5
Cr	0.4 ± 0.9	0.08 ± 0.2	0.08 ± 0.2	0.01 ± 0.02	0.04 ± 0.1

Manassas National Battlefield Park

MANA is located squarely in the center of the Piedmont region of Northern Virginia. Unlike the other parks of the Piedmont, however, the geology of MANA is unique in the NCRN. The park occupies an ancient lowland basin which was filled with silt and clay from the eroding Blue Ridge mountains. These clasts lithified into siltstones and shales which comprise the parent material of many of the MANA soils. Approximately 80% of the 19 total long-term vegetation monitoring plots in the park are composed of ancient alluvial shale and siltstone soil parent materials. The other MANA plots are underlain by parent materials of residual igneous diabase which formed when magma rose to the surface between the cracks of the overlying continental crust which was thin from the separation of Africa from Eastern North America.

Alfisols are the soil order found in 15 of the 19 plots. The other plots have Inceptisols formed from recent shale and siltstone alluvium carried by Bull Run—the biggest stream in the park. Six soil series are present at MANA: Aden, Albano, Bermudian, Dulles, Haymarket, and Manassas. Albano is the prevalent series found in 10 plots

Overall, MANA soils were characterized by heavy clay—the highest percentage of any park in the NCRN. On the opposite end of the spectrum, it had the lowest percentage of coarse fragments. The high clay is a function of the clay/siltstone parent materials and a warm wet climate suitable for the weathering of rocks into soil. The high clay in MANA affected all aspects of park's soil physical and chemical properties.

D_b values were greater in MANA than in all other parks except WOTR, and its infiltration rates were the second slowest in the region behind WOTR. MANA had the highest penetration resistance in the NCRN, but it also had the highest volumetric water content. Both of these properties are attributable to the high clay soil texture which leads to the formation of many micropores able to hold a significant amount of water. Not surprisingly, MANA also had the highest proportion of poorly drained soils in the NCRN. 58% of plots contained a soil with reduced redoximorphic conditions in the upper 50 cm of the soil profile.

Superlatives also characterized two chemical properties of MANA soils (Table 8). Extractable Mn and Mg levels were the highest or nearly the highest in the region in certain soil horizons. However, a lot of variation accompanied the high Mg and Mn values which suggests that there is a stark difference between Mg and Mn background levels in the diabase and siltstone parent materials in the park. Most of the other soil chemical characteristics were near the regional average for all parks and pH was between 5.1 and 5.5 throughout the profile.

Table 8. Soil physical and chemical characteristics in MANA.

Soil Variables	O horizon	A horizon composite	A horizon profile	B horizon	C horizon
n	1	19	17	18	1
Horizon midpoint	n.a.	n.a.	10 ± 6	55 ± 3	68 ± n.a.
Clay	n.a.	n.a.	23 ± 8	33 ± 13	32 ± n.a.
Coarse fragments	n.a.	n.a.	2 ± 5	4 ± 8	0 ± n.a.
pH	n.a.	5.1	5.2	5.5	4.8 ± n.a.
CEC	n.a.	13 ± 4.6	11 ± 3.8	12 ± 3.7	14 ± n.a.
BS	n.a.	61 ± 27	61 ± 27	61 ± 21	88 ± n.a.
Total C	29 ± n.a.	4.4 ± 2.1	2.6 ± 1.2	0.55 ± 0.32	0.77 ± n.a.
Total N	1.0 ± n.a.	0.28 ± 0.13	0.17 ± 0.09	0.06 ± 0.05	0.04 ± n.a.
P	66 ± n.a.	9.8 ± 4.3	7.9 ± 3.8	4.6 ± 3.7	4.0 ± n.a.
K	390 ± n.a.	100 ± 52	68 ± 31	38 ± 21	29 ± n.a.
Ca	1960 ± n.a.	1310 ± 807	991 ± 662	692 ± 487	989 ± n.a.
Mg	300 ± n.a.	240 ± 160	220 ± 220	390 ± 250	800 ± n.a.
Na	59 ± n.a.	36 ± 30	35 ± 33	60 ± 53	41 ± n.a.
Mn	610 ± n.a.	130 ± 71	89 ± 83	24 ± 23	16 ± n.a.
Fe	63 ± n.a.	79 ± 90	74 ± 110	28 ± 14	33 ± n.a.
Cu	1.1 ± n.a.	3.8 ± 5.0	5.9 ± 9.3	9.3 ± 22.1	1.0 ± n.a.
Zn	27 ± n.a.	5.7 ± 3.0	5.3 ± 5.1	3.4 ± 5.2	1.6 ± n.a.
Ni	3.2 ± n.a.	1 ± 1	1 ± 0.6	1 ± 0.7	2 ± n.a.
Mo	b.d.l.	0.1 ± 0.2	0.06 ± 0.1	0.06 ± 0.1	b.d.l.
Pb	2 ± n.a.	1 ± 1	1 ± 2	0.5 ± 0.4	0.2 ± n.a.
Cd	0.5 ± n.a.	0.1 ± 0.1	0.2 ± 0.5	0.2 ± 0.4	b.d.l.
Cr	b.d.l.	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	b.d.l.

Monocacy National Battlefield Park

Like MANA, MONO is found in the center of the Piedmont on the Maryland side of the Potomac River. Though some limestone is present in the park, the predominant soil parent material is metamorphosed slate, phyllite and schist. Of the soils in MONO's 15 long-term vegetation plots, 14 were formed from metamorphic residuum (either slate, phyllite or schist). One soil had alluvial parent materials located in a plot on the Monocacy floodplain, and one soil had a limestone parent material.

Three quarters of the park's soils are Ultisols, but there were also three Inceptisols, and one Alfisol. The park has 6 soil series: Baile, Cardiff, Comus, Glenelg, Hagerstown and Whiteford. More than half the soils (9 plots total) are from the Whiteford series.

MONO soils were rocky. They contained the highest percentage of coarse fragments in the NCRN, and consequently only 3 profiles were excavated to 100 cm depth. The coarse fragments undoubtedly affected penetration resistance which was higher than any other park in the region below 15 cm. Other physical characteristics in MONO were average for the region.

Though soils were rocky, the chemical data suggests that they are fairly fertile (Table 9). Total C, total N, extractable P and K were in the top third of soils in the NCRN. Extractable Ca was also above the regional average. The pH from A composite to B horizon ranged from 5.0 to 6.1, and soil contaminants were very low.

One plot, MONO-0044, contained 190 mg kg^{-1} extractable P in the E horizon (29 cm depth) when the other 3 plots with E horizons contained a maximum of 7 mg kg^{-1}. The soil in MONO-0044 was only able to be excavated to 37 cm, and the extractable P in the A composite horizon was 70 mg kg^{-1} when the park average for that horizon was 21 ± 15 standard deviation. The pH of the plot was also ≥6.4 which suggests that there is an unusual parent material in that plot which is affecting the soil properties of the entire profile. An alternative explanation is that perhaps there was an influx of wood ash or manure. We suggest further inquiry into the reasons for the abnormally high P values in MONO-0044.

Table 9. Soil physical and chemical characteristics in MONO.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	2	16	14	4	13	2
Horizon midpoint	11 ± n.a.	n.a.	12 ± 7	23 ± 5.4	44 ± 17	61 ± 10
Clay	n.a.	n.a.	15 ± 6	10 ± 4.3	22 ± 7.6	25 ± 13
Coarse fragments	n.a.	n.a.	27 ± 18	65 ± 22	38 ± 25	57 ± 13
pH	4.4	5.2	5.3	6.1	5.0	4.0
CEC	36 ± 2.2	19 ± 6.8	12 ± 6.2	9.1 ± 2.6	8.2 ± 3.3	7.2 ± 2.5
BS	87 ± 14	63 ± 23	53 ± 25	42 ± 37	42 ± 26	22 ± 11
Total C	24 ± 0.59	6.9 ± 3.8	4.5 ± 3.2	0.74 ± 0.26	1.4 ± 2.0	1.1 ± 0.6
Total N	1.6 ± 0.11	0.41 ± 0.15	0.29 ± 0.18	0.06 ± 0.02	0.09 ± 0.09	0.08 ± 0.03
P	92 ± 42	21 ± 15	15 ± 6.3	52 ± 80	7.1 ± 4.8	5.2 ± 1.7
K	450 ± 22	180 ± 62	120 ± 61	73 ± 36	62 ± 25	52 ± 17
Ca	5160 ± 551	1910 ± 1030	1080 ± 609	811 ± 1030	460 ± 303	161 ± 57.2

Table 9 (continued). Soil physical and chemical characteristics in MONO.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
Mg	520 ± 59	190 ± 74	120 ± 68	41 ± 27	64 ± 31	40 ± 7.0
Na	26 ± 3.5	23 ± 23	24 ± 34	9.3 ± 3.1	20 ± 24	14 ± 5.7
Mn	170 ± 77	71 ± 36	45 ± 15	22 ± 12	21 ± 14	10 ± 1.9
Fe	20 ± 13	57 ± 54	55 ± 32	23 ± 5.0	37 ± 29	21 ± 3.6
Cu	0.48 ± 0.10	6.1 ± 6.8	7.2 ± 5.5	9.6 ± 6.3	6.5 ± 5.3	4.6 ± 2.8
Zn	22 ± 1.5	10 ± 4.8	8.4 ± 4.8	7.8 ± 4.3	4.1 ± 2.6	2.1 ± 0.7
Ni	1.8 ± 0.52	1.3 ± 0.41	1.3 ± 0.83	0.8 ± 0.4	1.4 ± 1.3	1.9 ± 1.3
Mo	0.5 ± 0.01	0.06 ± 0.1	0.08 ± 0.1	b.d.l.	0.1 ± 0.1	0.08 ± 0.08
Pb	2.9 ± 0.84	1.9 ± 1.5	1.7 ± 1.5	0.8 ± 0.4	1.0 ± 1.0	1.3 ± 0.6
Cd	0.4 ± 0.06	0.4 ± 0.8	0.1 ± 0.1	0.03 ± 0.03	0.1 ± 0.1	0.1 ± 0.04
Cr	0.8 ± 0.01	0.1 ± 0.2	0.1 ± 0.1	b.d.l.	0.1 ± 0.1	0.04 ± 0.01

National Capital Parks-East

NACE is composed of a series of parks that form a modified semicircle from north to south around the eastern edge of DC and which continue to parallel the Potomac and Anacostia Rivers into southeastern Maryland. It is the only park unit in the NCRN located entirely on the Coastal Plain.

With the exception of a handful of plots on the Potomac River floodplain, the parent materials found in NACE are entirely ancient marine sediments deposited millions of years ago when seas covered most of Eastern Maryland. A total of 47 long-term vegetation monitoring plots were established in the park. Ultisols are the primary soil order in 81% of those plots. In the rest of the plots which are located on the floodplain, 2 soils are Entisols and 7 are Inceptisols.

Eighteen soil series are present in NACE: Chillum, Christiana, Croom, Dodon, Downer, Elkton, Fallsington, Fluvaquents, Hammonton, Hatboro, Howell, Ingleside, Muirkirk, Potobac, Sassafras, Udorthents, Wist, and Woodstown. Christiana is the most prevalent series in the park found in 25% of the plots. Potomac is the second most prevalent found in 13% of the plots.

The soils of NACE are some of the deepest in the NCRN and contain very few coarse fragments (Table 10). Marine sediment parent materials vary widely in texture from almost pure sand to clay which explains why clay percent ranged from 4 to 67% in NACE.

Soil physical values in NACE were mostly in the middle two thirds of NCRN park values. Penetration resistance in the top 15 cm was some of the lowest in the region, and all other values suggested the soils were adequately performing their intended ecosystem services.

Essential plant nutrient levels were often in the lower third of NCRN park values. This was true for most of the macronutrients: total N, extractable K, Ca, Mg, and for the micronutrient Mn. On the other hand, NACE's extractable Fe levels were the highest in the NCRN. Sandy parent materials and those with naturally low fertility are probably responsible for a large amount of the relatively poor nutrient status in NACE, compared to other parks and agricultural soils in the region.

Extractable Pb levels were higher in NACE than in any other park in the region. The fact that Pb levels are highest in the surface layers and decline throughout the profile suggests two things: first, that the levels are likely not tied to the parent material but rather come from automobile exhaust. (See Discussion Section.), and second, that Pb isn't leaching down throughout the soil profile. However, the levels are still well below the U.S. EPA residential soil screening level of 400 mg kg^{-1}. Nevertheless, these levels should be monitored in the future to determine if changes occur.

Table 10. Soil physical and chemical characteristics in NACE.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	11	48	37	5	47	4
Horizon midpoint	3.0 ± 2.0	n.a.	14 ± 7	32 ± 8.9	55 ± 18	86 ± 22
Clay	n.a.	n.a.	16 ± 6	7.4 ± 3.1	24 ± 10	14 ± 9.3
Coarse fragments	n.a.	n.a.	5 ± 9	11 ± 15	9 ± 16	4 ± 7
pH	3.2	5.4	6.0	4.0	6.1	5.6
CEC	100 ± 31	14 ± 7.1	12 ± 8.8	4.2 ± 2.1	8.9 ± 5.4	6.5 ± 2.7
BS	11 ± 6.4	42 ± 31	39 ± 31	15 ± 12	31 ± 31	52 ± 33
Total C	32 ± 7.3	4.8 ± 2.6	3.1 ± 2.5	0.68 ± 0.38	0.72 ± 0.78	0.33 ± 0.20
Total N	1.3 ± 0.39	0.27 ± 0.15	0.18 ± 0.11	0.03 ± 0.02	0.06 ± 0.07	0.04 ± 0.02
P	40 ± 15	11 ± 11	10 ± 12	8.8 ± 7.4	7.4 ± 12	17 ± 25
K	320 ± 150	85 ± 54	59 ± 45	18 ± 7.3	39 ± 33	64 ± 66
Ca	996 ± 587	844 ± 916	707 ± 919	57.3 ± 42.2	435 ± 922	589 ± 389
Mg	330 ± 130	110 ± 85	73 ± 65	17 ± 13	80 ± 130	100 ± 95
Na	90 ± 61	29 ± 32	22 ± 15	6.8 ± 3.2	23 ± 17	20 ± 8.5
Mn	98 ± 58	52 ± 49	41 ± 50	13 ± 8.5	13 ± 16	7.8 ± 5.2
Fe	180 ± 300	99 ± 160	110 ± 200	50 ± 22	63 ± 160	27 ± 19
Cu	6.5 ± 7.5	4.6 ± 4.1	7.6 ± 18	1.8 ± 1.2	5.8 ± 7.3	2.7 ± 0.9
Zn	29 ± 15	11 ± 17	11 ± 23	1.8 ± 1.4	7.1 ± 23	1.3 ± 0.5
Ni	4.7 ± 1.7	1.7 ± 1.1	2 ± 1	0.8 ± 0.8	1.5 ± 1.6	1.6 ± 1.1

Table 10 (continued). Soil physical and chemical characteristics in NACE.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
Mo	0.02 ± 0.05	0.02 ± 0.07	0.02 ± 0.08	b.d.l.	0.02 ± 0.05	b.d.l.
Pb	20 ± 11	10 ± 9.4	7.5 ± 9.5	3.5 ± 2.7	3.0 ± 8.9	0.5 ± 0.3
Cd	0.2 ± 0.2	0.2 ± 0.3	0.1 ± 0.3	0.04 ± 0.07	0.06 ± 0.1	0.03 ± 0.02
Cr	0.02 ± 0.05	0.07 ± 0.08	0.08 ± 0.08	0.05 ± 0.03	0.1 ± 0.1	0.1 ± 0.1

Prince William Forest Park

PRWI straddles the boundary between the Piedmont and the Coastal Plain at the southern end of the NCRN. The majority of its 5,089 ha however, are squarely in the Piedmont making it the largest protected Piedmont forest ecosystem in the United States. Pyrite mining played an important role in PRWI, and much of the park's land area was homesteaded or farmed into the 1930s. The forest ecosystem encompasses most of the watershed for Quantico Creek which meanders through the park.

With 145 long-term vegetation monitoring plots, PRWI is the second largest park in the NCRN. The soils in those plots can be divided into two classes: those formed on the Piedmont (90%) and those formed on the Coastal Plain (10%). Most of the Piedmont soils were formed from metamorphosed residuum: primarily gneiss and schist with some mafic rocks and quartzite scattered throughout. Micaceous minerals are common in the Piedmont soils. The Coastal plain soils were formed from Coastal Plain sediments. Some ancient and recent alluvial parent materials are also present in PRWI's plots. The recent materials are found on the floodplain adjacent to Quantico Creek.

Greater than 85% of the soils in PRWI plots are Ultisols. Inceptisols located on the floodplain comprise 7% of the plots, and a few Alfisols also exist in PRWI. Coastal Plain soil series found in the park are: Bourne, Dumfries, Neabsco, and Quantico. The Inceptisols all belong to one soil series, Hatboro. The Piedmont soil series from most to least prevalent in PRWI plots are: Meadowville (35 plots), Buckhall (22 plots), Elsinboro (22 plots), Glenelg (17 plots), Appling (7 plots), Orenda (4 plots), Spriggs (4 plots), Worsham (4 plots), and Ashlar, Baile, Occoquan with with ≤3 plots each. It is surprising that only 16 soils series are found in a park with 147 long-term plots. That fact gives PRWI the distinction of having the highest plot:soil series ratio in the NCRN.

The low soil series diversity was reflected in the relatively low variation in physical and chemical characteristics between plots within the park. Like MANA, PRWI was in the highest third of parks for clay percent and the lowest third for coarse fragments. D_b and penetration resistance were in the middle third of parks. Interestingly, infiltration rates were the second fastest in the NCRN, and θ_v pre and post infiltration were the lowest values in the region (post infiltration θ_v was significantly lower than 5 other parks). This indicates that PRWI's soils drain quickly, but also do not hold as much water in the surface as the other parks in the region. The predominantly loamy soil textures are probably responsible for the fast drainage and low water holding capacity.

Nearly all soil chemical values (Table 11) in all horizons were in the lowest third of NCRN park averages, and frequently the chemical property was the lowest in the region. PRWI's soils were quite acidic with pH values between 4.1 and 4.3 from surface to base of the profile. Base saturation (frequently used as an overall index of fertility, e.g., Perles et al. 2014) values were the lowest in the region. All parks in the NCRN, except WOTR, had at least double the extractable Ca of PRWI in the A composite horizon, and ANTI had close to an order of magnitude greater extractable Ca in the top mineral horizon. Levels of Total C, Total N, extractable P, K, and Mg also ranged from lowest to third lowest park values in the region. Only extractable Fe and Cu levels were in the highest third of parks. This is expected due to the underlying geology where pyrite (FeS_2) is a prominent mineral. One plot, PRWI-0537, contained 321 mg kg^{-1} extractable Cu in the C horizon making it an outlier among other PRWI plots. Copper deposits in sedimentary rocks can be found throughout Prince William County, Virginia, and the high levels in the bottom of the PRWI-0537 soil profile suggest that there might be a localized high ore deposit directly underneath this plot.

Table 11. Soil physical and chemical characteristics in PRWI.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	40	147	118	15	146	18
Horizon midpoint	2.0 ± 0.82	n.a.	11 ± 5	22 ± 9.4	52 ± 14	84 ± 14
Clay	n.a.	n.a.	19 ± 7	11 ± 3.9	27 ± 9.0	15 ± 11
Coarse fragments	n.a.	n.a.	7 ± 11	8 ± 14	8 ± 15	10 ± 20
pH	4.2	4.1	4.2	4.1	4.2	4.3
CEC	57 ± 25	12 ± 7.9	8.2 ± 5.1	6.4 ± 3.0	10 ± 5.0	8.0 ± 4.9
BS	23 ± 18	22 ± 18	20 ± 18	14 ± 11	20 ± 18	35 ± 19
Total C	28 ± 5.4	4.6 ± 2.9	2.6 ± 1.4	1.0 ± 0.5	0.5 ± 0.3	0.21 ± 0.19
Total N	1.0 ± 0.2	0.20 ± 0.12	0.12 ± 0.07	0.05 ± 0.03	0.03 ± 0.02	0.01 ± 0.01
P	33 ± 12	7.0 ± 4.4	5.1 ± 4.1	1.9 ± 0.9	2.6 ± 2.6	3.8 ± 2.2
K	420 ± 170	93 ± 60	63 ± 32	40 ± 25	44 ± 24	41 ± 18
Ca	1210 ± 1210	323 ± 393	161 ± 225	75.3 ± 74.8	122 ± 168	129 ± 185
Mg	350 ± 280	90 ± 89	57 ± 77	37 ± 59	120 ± 120	170 ± 130
Na	43 ± 30	18 ± 13	16 ± 10	12 ± 7.8	16 ± 10	17 ± 8.4
Mn	220 ± 160	58 ± 59	34 ± 32	18 ± 9.1	11 ± 12	16 ± 18
Fe	83 ± 40	81 ± 46	69 ± 59	40 ± 33	25 ± 52	18 ± 19
Cu	11 ± 14	4.3 ± 4.5	3.6 ± 4.9	3.4 ± 2.1	4.3 ± 17	19 ± 73
Zn	23 ± 18	5.8 ± 5.5	3.7 ± 5.3	2.2 ± 1.0	2.6 ± 7.1	6.3 ± 21

Table 11 (continued). Soil physical and chemical characteristics in PRWI.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
Ni	3 ± 1	1 ± 0.9	0.8 ± 0.5	0.5 ± 0.4	1.1 ± 1.0	1.3 ± 1.1
Mo	0.1 ± 0.3	0.04 ± 0.1	0.06 ± 0.2	b.d.l.	0.04 ± 0.08	0.04 ± 0.05
Pb	2.1 ± 1.3	3.0 ± 1.7	2.5 ± 1.9	1.8 ± 1.0	1.1 ± 0.6	0.5 ± 0.3
Cd	0.2 ± 0.3	0.09 ± 0.2	0.1 ± 0.5	0.1 ± 0.1	0.03 ± 0.05	0.03 ± 0.04
Cr	0.1 ± 0.2	0.09 ± 0.08	0.1 ± 0.1	0.1 ± 0.1	0.06 ± 0.07	0.1 ± 0.1

Rock Creek Park

ROCR is the third oldest national park in the United States (established in 1890), and the only park in the NCRN entirely within the bounds of Washington, D.C. It is also the only park that could be classified as an urban forest located entirely within the boundaries of a city. The park has long been an oasis for and destination for city dwellers and hosts heavy vehicle and pedestrian traffic on a daily basis.

Like PRWI, ROCR also straddles the border of the Piedmont and Coastal Plain, but resides mainly in the Piedmont. Rolling hills are the backbone of the park, and often they rise steeply from the banks of Rock Creek. The geology and soil parent materials in the 19 long-term vegetation monitoring plots are primarily residual metamorphic gneiss and schist with a high amount of micaceous minerals. These materials are found in 14 plots. Marine sediments from the Coastal Plain comprise the predominant parent material in 5 plots.

Four soil series are present in ROCR. Brandywine (5 plots), Manor (5 plots), and Glenelg (4 plots) are the series with metamorphic residuum parent materials. The Coastal Plain soils are all from the Sassafras series.

Horizon mean clay contents in ROCR were some of the lowest in the NCRN. The penetration resistance in the park was also the lowest in the region for the top 15 cm of the profile and the second lowest in the region from 20 to 30 cm. All other physical property averages were in the middle third of the region's parks.

ROCR was also in the middle third of park averages for almost every extractable plant nutrient (Table 12). Like GWMP, ROCR's soils could also be considered a "typical" soil of the region. It should be noted, however, that total C and total N in the B horizon were lower than 2/3 of the other parks. Behind NACE, Pb was also the second highest in the region in the mineral surface horizon, likely due to leaded gasoline used in pre-1990 vehicle traffic (see discussion in the NACE section).

Table 12. Soil physical and chemical characteristics in ROCR.

Soil Variables	O horizon	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	1	19	15	1	18	7
Horizon midpoint	n.a.	n.a.	12 ± 7	49 ± n.a.	51 ± 8.8	73 ± 29
Clay	n.a.	n.a.	16 ± 7	3 ± n.a.	17 ± 9.3	6.9 ± 3.3
Coarse fragments	n.a.	n.a.	9 ± 16	10 ± n.a.	10 ± 14	28 ± 29
pH	n.a.	5.7	5.8	4.2 ± n.a.	4.7	4.4
CEC	n.a.	13 ± 6.2	13 ± 11	5.4 ± n.a.	8.5 ± 3.3	6.3 ± 3.1
BS	n.a.	46 ± 28	43 ± 30	8 ± n.a.	31 ± 25	39 ± 25
Total C	35 ± n.a.	4.7 ± 2.3	4.1 ± 3.7	0.56 ± n.a.	0.42 ± 0.26	0.69 ± 1.4
Total N	1.5 ± n.a.	0.26 ± 0.12	0.29 ± 0.39	0.04 ± n.a.	0.04 ± 0.03	0.03 ± 0.05
P	75 ± n.a.	13 ± 17	14 ± 22	5.3 ± n.a.	5.8 ± 5.6	5.1 ± 2.5
K	650 ± n.a.	120 ± 51	100 ± 71	41 ± n.a.	60 ± 21	56 ± 26
Ca	1360 ± n.a.	958 ± 908	895 ± 1390	39.3 ± n.a.	303 ± 330	180 ± 104
Mg	300 ± n.a.	160 ± 100	170 ± 260	12 ± n.a.	120 ± 129	99 ± 49.7
Na	74 ± n.a.	21 ± 11	20 ± 13	6.9 ± n.a.	17 ± 8.4	13 ± 4.7
Mn	160 ± n.a.	66 ± 41	75 ± 70	14 ± n.a.	22 ± 21	12 ± 5.6
Fe	94 ± n.a.	59 ± 50	64 ± 77	22 ± n.a.	36 ± 77	27 ± 38
Cu	1.9 ± n.a.	3.2 ± 3.1	4.5 ± 6.3	1.2 ± n.a.	3.5 ± 2.9	0.6 ± 0.4
Zn	24 ± n.a.	7.3 ± 4.5	8.5 ± 11	1.0 ± n.a.	3.6 ± 4.2	1.5 ± 0.8
Ni	4.1 ± n.a.	1.9 ± 1.8	1.6 ± 0.8	0.7 ± n.a.	1.6 ± 1.2	1.5 ± 1.0
Mo	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.02 ± 0.06	0.01 ± 0.02
Pb	11 ± n.a.	7.9 ± 7.2	4.5 ± 3.6	1.1 ± n.a.	1.5 ± 1.2	2.3 ± 4.0
Cd	0.3 ± n.a.	0.1 ± 0.08	0.06 ± 0.06	b.d.l.	0.2 ± 0.3	0.05 ± 0.06
Cr	0.1 ± n.a.	0.09 ± 0.08	0.1 ± 0.1	0.1 ± n.a.	0.1 ± 0.2	0.06 ± 0.05

Wolf Trap National Park for the Performing Arts

At 43 ha, WOTR is the smallest national park in the NCRN. It is located in the Piedmont region, and a stream, Wolf Trap Run, cuts through the park.

There are only six long-term vegetation monitoring plots in WOTR. Glenelg, which is comprised of schist residuum parent materials, is the predominant soil series in 5 plots. The Codorus soil series formed from schist and quartzite alluvium is found in the 1 plot located on Wolf Trap Run's floodplain. This soil is classified as an Inceptisol and the other 5 soils in the park are Ultisols.

WOTR's soils had the highest D_b in the NCRN. Moreover, they also had the slowest infiltration rates. The penetration resistance values are also some of the highest in the region. These data suggest that the park struggles with compacted soils. This could increase the risk to vegetation health and also the erosion potential in the park leading to stream degradation. We suggest that these factors be monitored to prevent undue damage from compaction.

The soil chemistry and fertility patterns in WOTR (Table 13) were very similar to those in PRWI. WOTR soils are quite acidic with a pH between 4.1 and 4.6 in all horizons. In the A and B horizons, Total C was the lowest in the region. For Total N and the extractable macronutrients, WOTR's levels were either the lowest or second-to-lowest (behind PRWI) among the parks in the region. Extractable Mn and Zn values were also low. Only extractable Fe and Cu were above average in the region. Cu was the highest in the NCRN in the A and B horizons and extractable Fe was in the highest third of parks in the A composite horizon.

The combination of poor physical and chemical characteristics in WOTR should monitored to ensure that they do not interfere with ecosystem function in the park.

Table 13. Soil physical and chemical characteristics in WOTR.

Soil Variables	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
n	6	4	1	4	2
Horizon midpoint	n.a.	8 ± 3	42 ± n.a.	47 ± 14	70 ± 11
Clay	n.a.	16 ± 6	8 ± n.a.	27 ± 5.1	8.9 ± 1.1
Coarse fragments	n.a.	6 ± 9	50 ± n.a.	10 ± 10	30 ± 10
pH	4.6	4.2	4.6 ± n.a.	4.1	4.2
CEC	9.0 ± 4.1	5.8 ± 1.2	4.1 ± n.a.	6.0 ± 0.3	4.3 ± 0.6
BS	38 ± 29	36 ± 20	32 ± n.a.	22 ± 7.8	24 ± 0.9
Total C	3.7 ± 1.0	2.5 ± 0.26	1.0 ± n.a.	0.38 ± 0.04	0.13 ± 0.003
Total N	0.20 ± 0.05	0.16 ± 0.02	0.06 ± n.a.	0.04 ± 0.01	0.02 ± 0.0
P	6.2 ± 1.7	5.1 ± 0.7	1.4 ± n.a.	2.5 ± 0.2	2.1 ± 0.14
K	74 ± 22	56 ± 9.5	52 ± n.a.	34 ± 8.8	25 ± 6.9
Ca	428 ± 346	286 ± 190	137 ± n.a.	138 ± 80.1	101 ± 14.2
Mg	73 ± 60	52 ± 26	50 ± n.a.	49 ± 11.3	47 ± 4.4
Na	20 ± 17	21 ± 19	16 ± n.a.	18 ± 12.1	12 ± 1.8
Mn	38 ± 27	38 ± 15	26 ± n.a.	8.0 ± 3.4	16 ± 7.2
Fe	99 ± 66	53 ± 16	30 ± n.a.	20 ± 6.9	12 ± 2.0

Table 13 (continued). Soil physical and chemical characteristics in WOTR.

Soil Variables	A horizon composite	A horizon profile	E horizon	B horizon	C horizon
Cu	7.6 ± 3.3	7.1 ± 2.5	2.1 ± n.a.	9.6 ± 7.7	2.3 ± 0.65
Zn	6.1 ± 2.2	5.9 ± 3.1	1.1 ± n.a.	3.8 ± 3.2	1.4 ± 0.2
Ni	1 ± 0.2	0.6 ± 0.1	0.7 ± n.a.	0.4 ± 0.1	0.3 ± 0.02
Mo	b.d.l.	0.03 ± 0.06	b.d.l.	b.d.l.	b.d.l.
Pb	6.4 ± 5.0	6.5 ± 5.4	1.6 ± n.a.	1.6 ± 0.4	1.0 ± 0.5
Cd	0.5 ± 1.2	0.09 ± 0.07	b.d.l.	0.04 ± 0.03	0.1 ± 0.0006
Cr	0.03 ± 0.04	0.03 ± 0.02	0.07 ± n.a.	0.01 ± 0.01	b.d.l.

Discussion

NCRN soils data in the context of the I&M program

Soil Resources is one of the twelve basic Natural Resource Inventories identified by NPS to help park managers "understand and manage park natural resources." (NPS 2019a). However, a search of each I&M website for all 32 networks (accessed 26 May 2019) reveals that over half (including NCRN) have either not yet collected or not yet published their own field-derived soil dataset. Six networks have a Soil Resources Inventory (SRI) from the National Cooperative Soil Survey (NCSS)—a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies including the Agricultural Experiment Stations, and local agencies; it is unclear whether those six networks plan to instate their own monitoring program. Moreover, only 91 of greather than 400 NPS units monitor "soil functions and dynamics" which includes soil nutrients, biological soil crust communities, and soil aggregate stability (Fancy and Bennetts 2012).

Of the published soils reports from I&M networks, this is the first to examine such an extensive suite of physical and chemical properties. I&M networks typically report on aggregate stability, compaction, and bulk density, but to the best of our knowledge, no networks have measured infiltration or penetration resistance. In addition, for soil chemical variables, most networks restricted themselves to total C, total N, pH, CEC and BS, and no network has published the breadth of macro or micronutrient data recorded in this report. Some networks focus on ecosystem-specific soil measurements important to their region, e.g., biological soil crust cover in the Chihuahuan Desert, electrical conductivity (EC) in Sonoran Desert, or soil surface elevation in South Florida/Caribbean (McIntyre and Studd 2013; Pan et al. 2015; Whelan and Smith 2006), but none has combined chemical and physical measurements with a soil profile description to a depth of 100 cm.

Furthermore, NCRN collected data from 426 plots, whereas typically networks collected many fewer samples. Only Eastern Rivers and Mountains Network (ERMN) with 348 plots came close to the number of plots in the NCRN (Perles et al. 2014). This report, therefore, is novel within the context of the national I&M program not only for the number of soil variables measured, but also for the sheer volume of data collected. It was the intent of the NCRN to inventory as many soil variables as possible in anticipation of discovering new and meaningful insights into the Eastern Deciduous Forest Ecosystem function (air, water, flora, fauna).

NCRN soils data in the context of Eastern Deciduous Forests

Relatively few forest soil studies have been conducted in the Mid-Atlantic region. None measures the entire suite of chemical and physical variables covered in this report and to the best of our knowledge only one (McGarvey et al. 2015) covers the 4 physiographic provinces that the NCRN surveyed. Consequently, in addition to its value within the NPS I&M Program, this report represents an important, unique and extensive survey of Mid-Atlantic forest soil chemical and physical properties.

To date, forest soil research in the Mid-Atlantic has primarily been conducted at two locations: the Smithsonian Environmental Research Center (SERC) on the Coastal Plain in Anne Arundel County, MD (see McGarvey et al. 2015; Szlavecz et al. 2011; Yesolinis et al. 2016) and the Fernow Experimental Forest on the Allegheny Plateau in Tucker County, WV (see Adams et al. 1997;

Gilliam et al. 1994, 2001). Those studies targeted specific components of forest soil ecosystems, (e.g., earthworm dynamics, historical land use, carbon storage, and nitrogen saturation). This report, however, serves three critical purposes for the Mid-Atlantic region: 1) it fills a void in the literature by answering a sometimes overlooked but fundamental ecological question, "What is there?"; 2) it lays a solid foundation for many future ecological studies; 3) it provides easily accessible soil physical and chemical data, horizon by horizon, to depths not frequently sampled.

NCRN soil patterns and ecological insights

The NCRN soils data reveals several important ecological patterns and insights. The first is that contrary to expectations based on the urban nature of the region, there are relatively few heavy metal contaminants (Cd, Cr, and Pb). It is not surprising that NACE and ROCR had the highest levels of Pb, given that these parks are situated in urban centers in close proximity to roads with heavy vehicle traffic. This suggests that pre-1970s leaded gasoline is primarily responsible for soil Pb and further attested to by the fact that Pb concentrations declined with depth (Erel et al. 1997). However, even the highest levels of extractable soil Pb are an order of magnitude below the EPA soil screening level of 400 mg kg^{-1}—the recommended limit for safe residential use (EPA, 2019). Nonetheless, it must be noted that the screening levels are developed for total levels of contaminants (i.e., the weight contaminant/weight soil) not extracted levels of Pb. Thus, those specific plots with noted high levels of Pb, Cd or Cr in the "Park overviews" section, might warrant further testing for total contaminant levels to determine if soil levels are considered safe for accidental ingestion. Future monitoring should also determine whether Pb moves deeper in the soil profile over time as Johnson and Richter (2010) found in other forest soils of the Mid-Atlantic.

Another insight is that parent materials appear to have the greatest effect on soil chemical variables throughout the region. Though important variables such as landscape position, elevation, slope aspect, and the effect of soil micro- and macro-organisms were not characterized in this study, and thus we cannot determine their relative effect on soil chemistry (For an example of this approach, see Perles et al. 2014.), the data point to a strong parent material effect. This finding is attested to by the fact that a park with the highest levels of a nutrient in its upper horizons compared to other parks' upper horizons, typically had the highest or nearly highest level of that nutrient in its lower horizons compared to other parks' lower horizons. The same phenomenon held true for parks with the lowest levels of nutrients in all horizons. The parks typically maintained their relative level of nutrients compared to other parks throughout the entire profile. For example, ANTI and MANA had the highest levels of extractable K and Mn respectively in their A and B horizons of any park in the region. PRWI and NACE had the lowest levels of Mg in their A and B horizons throughout the region. Since ANTI in the Appalachian Valley is largely underlain by a parent material not found in many of the other parks—limestone. MANA is underlain by rocks high in Mn, and PRWI and NACE are largely formed from acidic, quartzite parent materials. This suggests that parent materials are responsible for the observed patterns.

Interestingly, the homogeneity of relative nutrients throughout the profile also suggests that though parks are often defined by political boundaries, this delineation appears to be an ecologically significant grouping mechanism for NCRN soils. Soils within a park boundary typically have similar

parent materials. This is a fruitful area for future study. It also suggests that because parent materials have such a strong effect on relative nutrient levels throughout the profile, future sampling events for plant available nutrients can focus on the soil surface. Surface values can be used to estimate nutrients lower in the profile based on the magnitude of decrease or increase from upper to lower horizons.

The vertical distribution of nutrients in the soil profile revealed another important NCRN pattern. Most soil properties are strongly linked to horizon and more soil studies should focus on the soil horizon concept of sampling. Moreover, the highest levels of both macro and micronutrients were found in the O horizon, underlain by high nutrient levels in the A composite horizon, and a frequent noticeable decrease in nutrients between A composite and A horizon samples. This suggests that nutrient levels change very rapidly in the top 30 cm of the soil surface (the typical maximum depth of cumulative A horizons). It further suggests that sampling by horizon and by arbitrary depth (e.g., 15 cm as was used for composite sampling) tell different ecological stories, and that both are important when considering ecology and landscape trends. If depth and horizon are not both taken into account, the sampling will be fraught with the possibility of seriously over or underestimating nutrients. Though the scientific literature points to higher concentrations of nutrients in the surface than in lower forest soil horizons (see summaries in Johnson and Lindberg 1992; Weil and Brady 2017), the very high surficial levels of a broad suite of nutrients suggests that nutrient cycling from organic material—specifically the decay of leaf, twig and root litter—is the driver of vegetative growth in the region. Further studies are needed to confirm this hypothesis in the NCRN. Moreover, because NCRN nutrient distribution below the A horizon decreased slightly with depth but was overall fairly homogenous, these data further suggest that future sampling activities that correlate vegetation growth and soil properties should focus on the surface horizons. However, since we found noticeable differences between composite (surficial) and profile A samples (usually from deeper in the horizon) more research is needed to determine the very specific changes that occur with depth in the top 30 cm of a forest soil.

Surprisingly, only a little over quarter of NCRN plots have an O horizon. This raises several intriguing ecological questions: why do so few plots have O horizons? What factors in the region lead to robust O horizons? Is vegetative growth retarded by the lack of an O horizon? In a study conducted at SERC in MD, soil properties were measured in virgin (uncut) forests and those that were converted from agricultural use 50–70 years ago or 120–150 years ago (Yesilonis et al. 2016). The authors found that the most prominent difference between the treatments was the presence or absence of a well-developed O horizon. The uncut forests had a thick O horizon, the 120–150-year old forests had a small or nonexistent O horizon, and the 50–70-year old forests had absolutely no O horizons. This indicates that many of the soils in the NCRN have not had enough time to develop O horizons and offers another fruitful opportunity for future studies. Yesilonis et al also found that soils in uncut stands were significantly more acidic than the older secondary forests, which in turn were significantly more acidic than the younger secondary forests. The uncut forests had higher soil C and lower bulk density compared to the other two treatments. This suggests that time is a very important controlling factor for forest soil dynamics in the region, and also that NCRN soils could continue to

sequester carbon over multiple century timescales. It also highlights the need for continued monitoring to track these changes.

Future directions

Throughout the Discussion section, we have identified areas for fruitful future studies. This section highlights the gaps and limitations of this data set and recommends four major objectives for future studies.

Soil formation is a function of five independent factors which work in tandem to determine soil properties observed in the field: climate, parent material, time, relief, and organisms (Jenny 1941). Data on the last formation factor, organisms, is entirely missing from this data set, and thus presents a major gap in the NCRN soil survey. Though aggregate stability is heavily influenced by microorganisms, there are no direct measures of this very important component of soil science. Moreover, soil biology is at the center of nutrient cycling, ecosystem function, and soil health; biological properties should be assessed and integrated with chemical and physical measurements. Recommended soil biology tests include active carbon, soil respiration, soil proteins, and potentially mineralizable nitrogen (Islam and Weil 2000; Moebius-Clune et al. 2016).

Other I&M networks on the East Coast (ERMN and Appalachian Highlands Network) focused soil monitoring efforts on sulfur (S) and nitrogen (N) pollution (Perles et al. 2014; Sullivan et al. 2011). Sulfur was not evaluated in this study, nor did we attempt to determine N saturation. However, according to a report published by the Appalachian Highlands Network that evaluated the sensitivity of I&M parks to acidification and S and N pollution from the atmosphere, the NCRN ranked 2nd among the country's 32 regions in the Pollutant Exposure category (Sullivan et al. 2011). This high ranking undoubtedly stems from the NCRN's proximity to urban and industrial centers. We recommend that future monitoring efforts assess S levels as well as nitrate fluxes to determine whether the NCRN's soils are at risk from these potential pollutants.

Future studies are also needed to determine not only the pool of extractable nutrients in the NCRN at single point in time (assessed in this study) but also their fluxes and how these fluxes are affecting vegetation growth. It remains a challenge to measure the flux of nutrients into the soil pool from decaying organic material (leaves, twigs, rotting wood) and inorganic mineral sources and out of the pool through plant uptake or leaching, and whether these nutrients are limiting vegetation growth. Nevertheless these biogeochemical studies are vital to understanding healthy ecosystem function (Fisher and Binkley 2000).

The soil C data in this study can be used to assess soil C stocks (megagrams of C per unit area to a depth of 100 cm) in the NCRN (i.e., how much carbon is sequestered in the region's soils). This computation is a very important part of quantifying the impact that these urban forests can have on mitigating CO_2 emissions. Lal (2005) found that temperate forest soils contain 69% more C than the vegetation (100 compared to 59 Pg) which attests to the importance of forest soils for long-term CO_2 reduction strategies. Moreover, Yesilonis et al. (2016) discovered that the soil C in 120–150-year old secondary forests at SERC in MD was significantly greater than in the 50–70-year old stands. McGarvey et al. (2015) likewise found that total C density was 30% higher in old growth forests than

in secondary forests. These studies suggest that the value of the NCRN forest soils for combating climate change will only increase.

Many other scientifically important questions can be addressed with this data, including: do differences in nutrient concentrations among parks have any significance for ecosystem function? Do low pH values across the region reduce fine roots (a pattern observed by McNulty et al. (2007) and Vanguelova et al. (2007), and caused by high aluminum and depletion of calcium and magnesium)? In sum, the soils data collected in this report lay a solid foundation for future monitoring activities and shed light on the condition of NCRN soils. It is the sincere hope of the authors that this report will aid other I&M networks in their soil monitoring efforts and will advance the science of forest ecology in the Mid-Atlantic region.

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Appendix A

Definition of Soil Terminology

This appendix contains definitions of terms used in this report and general vocabulary germane to soil science. The definitions presented here are summaries from Weil and Brady (2017) and Soil Taxonomy (Soil Survey Staff 2014b). When abbreviations were used for workbook soil terms, the abbreviation is given in parentheses after the soil term, e.g., "cobbles" (CB). The definitions of certain soil properties are nested within the overarching term. For example, specific horizon designations (O, A, E, B, C, R) are explained nested underneath the word "Horizons." Any general soil terminology used in this report is also defined, and every effort was made to give examples and explain terms within the context of the NCRN. Terms appear in alphabetical order unless otherwise noted.

Definitions

Aggregate stability – An important test of the cohesion of an aggregate (a mass of soil particles held together in a cohesive shape) from the surface of the soil. Aggregate stability is measured on a scale from 1 to 6 (least to most cohesive respectively) when it is immersed in water. If the aggregate slakes (falls apart) quickly after being placed in water, it is poorly cohesive. Aggregate stability is very responsive to human management, and typically is closely related to soil carbon content and inversely related to compaction.

Base Saturation – The percent of the CEC occupied by base (non-acid) cations: Ca, Mg, K, and Na. It is sometimes used as a proxy for fertility.

Boundary description – Profile descriptions note the base of each horizon. However, horizons transitions are typically not defined by clear lines but rather change more gradually over a certain depth. The boundary descriptions (abrupt {A}, clear {C}, gradual {G}, diffuse {D}) describe the relative definition of the boundary from a strong, easily distinguished boundary to a boundary that shows a lot of variation respectively.

Bulk density (D_b) – The dry weight of the fine earth fraction of soil divided by the entire volume that the fine earth fraction occupies (including pore spaces). D_b can be used to calculate the pore space of the soil because soil scientists frequently assume a fixed particle density (D_p) of 2.65 g cm^{-3} for the soil solids (mainly quartz-based particles east of the Mississippi). Percent pore space = $1 - D_b/D_p$.

CEC – The cation exchange capacity (CEC) of a soil measures the total amount of exchangeable cations (Ca, Mg, K, Na) present in an acid soil extractant (Mehlich 1) in addition to exchangeable H (determined by titration with 0.023 M Ca(OH)2) and expressed as milliequivalents per 100 g soil. CEC typically increases with clay and organic carbon content, but is also heavily influenced by the mineralogy of the clay particles.

Class – The three main categories of rock—sedimentary, metamorphic, or igneous—that characterize the PM rocks in a profile. If the PM was marine sediments or if the predominant rock/s was not discernable from Web Soil Survey, then this category was left blank.

Clay percent – Clay particles have a diameter <0.002 mm in diameter. With an enormous surface area (a fixed mass of clay particles can have a surface area hundreds of thousands of times greater than the same mass of sand particles) the clay percentage has a very strong effect (greater than that of sand and silt) on many physical and chemical soil processes such as the bulk density, penetration resistance, water infiltration and storage, carbon storage, etc.

Coarse fragments – Solids larger >2 mm in diameter within the soil profile. These are not considered part of the fine earth fraction (soil particles <2 mm in diameter) and thus do not factor into a determination of soil textural class. Four types of coarse fragments are found in the NCRN in order of their size from smallest to largest:

- **Gravel (GR) –** Coarse fragments that are 2 to 75 mm along their greatest diameter.
- **Cobbles (CB) –** Rounded coarse fragments that range from 75 to 250 mm along their greatest diameter.
- **Channers (CH) –** Flattened coarse fragments that range from 75 to 250 mm along their greatest diameter.
- **Flags (FL) –** Flattened large stones ranging from 150 to 380 mm along their greatest diameter.

Color (Hue, Value, Chroma) – Soil color is determined using the Munsell Color system with a hue, value and chroma (e.g., 10YR 4/6). Hue (the first symbol in a Munsell scheme—the "10YR" in the previous example) corresponds with the wavelength of light reflected off the soil. Value indicates how light or dark the soil sample is. The lower the value, the darker the color, and soil samples with values ≤3 are typically found in A or O horizons where organic carbon darkens the soil. The last number in the Munsell color designation, chroma, shows the saturation or brightness of the color. High chromas indicate well oxidized conditions. High values (≥4) and low chromas (≤2) indicate gleyed, reducing conditions when water saturates the profile for a significant period of time, and microorganisms reduce iron from its ferric to ferrous state causing it to become soluble and move to another part of the soil profile, leaving the uncoated mineral particles which appear colorless or gray to human eyes.

Consistency – The ease with which a soil aggregate ruptures when crushed between thumb and forefinger.

Contaminants – The extractable levels of 3 soil contaminants (Cd, Cr, Pb) most often associated with industrial or residential use were measured. High levels of these contaminants could detrimentally affect biological function for living organisms.

Gravimetric water content (θg) – A measure of the weight of water per weight of dry soil sample. This is measured by taking a soil sample, sieving out particles > than the fine earth fraction, weighing

the sample fresh, then drying the sample for 24 hours at 105ºC before weighing the sample dry. θg = (weight fresh sample – weight dry sample)/weight dry sample.

Horizons (Master Horizons) – Soil layers of varying thickness that run roughly parallel to the soil surface and occur due to soil-forming processes (losses, additions, translocations, transformations). As naturally occurring bodies in an ecosystem, soils are divided into and described according to the sequence of their horizons from the soil surface down to the parent material from which the soil formed. Every horizon consists of a master variable, either an O, A, E, B, or C (called the master horizons) denoted by a capital letter. The following descriptions of the master horizons appear in the order that these horizons would be found in a typical profile sequence from the soil surface to bedrock.

- **O horizons** are typically found at the soil surface in forest environments (and wetland environments where decomposition occurs slowly) when the soil is covered by a blanket of leaves (often described as the duff layer). Forested O horizons are directly underneath the layer of loose leaves and consist of predominantly organic materials (decomposing leaves forest debris) usually mixed with some mineral material. These horizons frequently increase water infiltration helping reduce erosion and are an important source of carbon and nutrients for soil micoorganisms and forest vegetation.
- **A horizons** are the topmost predominantly mineral layers near the soil surface that contain a high amount of organic matter and are therefore usually dark in color. In lay terms, an A horizon roughly corresponds with the term "topsoil" and have high fertility, high root density, and high numbers of soil microorganisms.
- **E horizons** are characterized by losses (eluviation) of soil materials—clay, Fe and Al oxides, nutrients, organic matter—and typically are found beneath an A horizon in acidic forested soils where materials leach through the E to the lower horizons. E horizons are usually lighter in color than the overlying horizons and are not accompanied by a subordinate horizon designation.
- **B horizons** are commonly associated with the term, "subsoil." They are layers typically characterized by accumulation (illuviation) of soil materials from the horizons above—clay, salts, iron, sulfates, carbonates, nutrients—that settle out beneath the O, A, and E horizon. B horizons must have a subordinate horizon designation next to them.
- **C horizons** are the bottommost layers of the soil profile which have been little affected by the soil forming processes that shaped the horizons above it. Often they resemble the parent material from which they formed and therefore consist of a large volume of rock or sand, whatever the original parent material was.
- **R** signifies bedrock and is not technically classified as soil, i.e., there are no physical or chemical descriptions.

Infiltration – Water entering the surface of the soil. In the NCRN, infiltration was performed on all soils without prior wetting (unsaturated), and then a second infiltration was performed (saturated)

after the first meaning that the soil was fully moistened with the same amount of water at all sites prior to the saturated infiltration.

Lithologic discontinuity – These are zones in a soil profile that represent a change in the parent materials from which the soil formed. For example, alluvial soil materials are frequently deposited on top of residuum. The interface of the two differing soil materials is the lithologic discontinuity, and there can be multiple discontinuities in a soil profile.

Nutrients – There are 14 essential nutrients that plants take up from the soil (meaning that without them a plant will not survive). Six of these nutrients (N, P, K, Ca, Mg, S) are referred to as macronutrients because plants use a relatively large amount of them (they make up >0.1% of the plant dry mass), and the others are considered micronutrients. The NCRN dataset includes the extractable levels (extracted using a strong acid solution) but not the total amount (with the exception of N) of 5 macronutrients (excluding S) and 7 micronutrients (Cl, Cu, Fe, Mn, Mo, Ni, Zn). In general, higher extractable levels of each nutrient (especially the macronutrients) indicates a healthier soil.

Order – The most general category of Soil Taxonomy, orders are primarily distinguished by the presence of specific diagnostic horizons. There are 12 soil orders in the world and five in the NCRN:

- **Alfisol –** These soils usually form under broad-leafed forests and in some grasslands. Like Ultisols, the Alfisols contain illuviated clay but are less weathered than the Ultisols, less acidic, and typically quite fertile for plant growth.
- **Entisol –** Soils that contain very little profile development. These soils do not have a B horizon because the environment is too extreme (e.g., insufficient water and cold temperatures) for them to form or because new parent materials or other disturbances are constantly resetting the soil forming processes. Often these soils are found in the mountains or directly next to a river where constant flooding changes the soil profile.
- **Inceptisol –** These are young soils (from the Latin inceptus) that have not had a lot of time for soil forming processes to delineate strong horizons. They therefore do not have many diagnostic features like a high presence of illuviated clay. Often Inceptisols will be found on a stream terrace or at the base of an eroded hill where an influx of parent materials in the not-too-distant past reset the soil forming clock.
- **Mollisol –** Soils with a thick surface horizon containing a high amount of organic carbon. They typically are found under grasslands where root turnover leads to a large influx of soil organic carbon but can also be found near rivers or in wetlands where a lack of oxygen impedes organic matter decomposition.
- **Ultisol –** Highly weathered soils that formed in forests of the humid tropics and subtropics. They contain illuviated (moved down from the horizons above) clay, are found throughout the southeast U.S., and are more acidic and typically less fertile than Alfisols.

Parent Material (PM) – The material from which a soil formed. The NCRN contains a diverse array of PMs:

- **Alluvium –** Water-deposited PM from a river or stream. Alluvium can be transported and deposited many miles from its original source and often produce highly fertile soils. Frequently alluvial materials are high in silt which is readily transported by water.
- **Colluvium –** Gravity-deposited PM (rocks, sand, etc) that is typically found in valleys or downslope from the summit of a hill or mountain.
- **Marine and sandy sediments –** PM deposited by ancient seas on top of the Coastal Plain. These materials are texturally diverse from very sandy to very clayey.
- **Residuum –** the bedrock that underlies a soil formed in place, i.e., residual PM is frequently found in upland areas where other wind, water, or gravity-deposited PMs have not been deposited overtop of the underlying bedrock.

Penetration resistance – A measure of the ease of penetrating the soil (in kPa) with a narrow rod capped by a cone-shaped head. This test is an indirect measure of soil compaction and can indicate how quickly water can enter a soil or the corollary—whether water might run off the surface causing erosion—or whether plant root growth will be impeded.

pH – The negative log of the hydrogen ion activity in the soil solution. This master variable controls many soil chemical and biological processes, especially the availability of plant nutrients for uptake and whether Al might be toxic to plant growth. Very acid soils or basic soils typically impede vegetative growth. pH was measured using a CaCl2 solution.

Profile – The sequence of horizons described from the soil surface to bedrock or whatever depth is excavated.

Region – Describes the physiographic province (Coastal Plain, Piedmont Plateau, Blue Ridge, or Ridge & Valley) where the soil plot is located. If the plot was located on a floodplain or stream terrace (regardless of province), then "stream terrace" or "floodplain" were noted in this category. The rationale is that a floodplain or stream terrace would have a greater effect on the nature of the sample than the physiographic region.

Rock – Refers to the predominant rock/s that comprise the PM. If the PM was marine sediments or if the predominant rock/s was not discernable from Web Soil Survey, then this category was left blank.

Series – The most specific category of the Soil Taxonomy system that identifies a soil based on specific diagnostic features localized to a certain geographic location (e.g., Myersville). There are over 23,000 soil series in the U.S. Each one can be likened to a species in the animal kingdom having all the characteristics that distinguish it from other soil series with sufficient geographic distribution to merit its own unique series classification.

Soil Taxonomy – The system of soil classification developed by the United States Department of Agriculture (USDA) in conjunction with the National Cooperative Soil Survey (NCSS) and used in the U.S. and other countries to group soils according to measurable, diagnostic properties (e.g., clay

content and chemical characteristics). There are six levels of soil taxonomy (from general to specific respectively): order, suborder, great group, subgroup, family, series.

Structure (type, size, grade) – Typically, soil particles clump together to form aggregates or peds based on the texture, carbon content, climate, etc., but in some very sandy conditions or in soils with lots of Na, the mineral particles stay in a loose non-aggregated condition. Soil texture describes the arrangement of the soil particles; the structure type designates the predominant shape of the peds; the size indicates how small or large the peds are (from very fine to very coarse); the grade indicates how distinct the structure is within the horizon (1 through 3 from not distinct to very distinct). Structure types within the NCRN are:

- **Granular (GR) –** spheroidal condition typically found in the surface A horizons where high carbon contents, plant roots, and macro and microfauna combine to form this structure.
- **Platy (PL) –** Stacked structure into pancake-like sheets. This structure is often a result of compacted conditions near the surface of the soil.
- **Prismatic (PR) –** Knife-like structure units where length of the ped is greater than width. Often found in horizons with a fragipan (Bx).
- **Subangular or Angular Blocky (SBK or ABK respectively) –** The most common structure of illuviated clay (Bt) horizons. This structure is cube shaped but greater in width than length. Subangular blocks have more round edges.

Subordinate horizon designations – These lower case letters are placed after the capitalized master horizons and detail the specific nature or a predominant characteristic of the master horizon (e.g., Bt). For example, the "t" subscript following a "B" master horizon indicates the presence of silicate clays in the B horizon. Subordinate horizon designations (with a few exceptions) are specific to particular master horizons. For example, the "p" subscript (denoting a plowed horizon) is only found after the A master horizon found at the surface of the soil profile. Multiple subordinate horizon designations may be combined after a master horizon (e.g., Btg). Subordinate horizon designations found in the NCRN are:

- **b –** Indicates that the horizon is buried underneath other layers and most often seen with A horizons (The b subordinate horizon typically occurs in zones that are flooded by rivers or streams).
- **c –** Indicates the presence of concretions or nodules (minerals or elements e.g., iron, that have moved down into the profile and solidified as little masses within the profile).
- **g –** Most often found next to a B horizon but can also be present with an A or C horizon, the g signifies gleying (gray colors) conditions when high water tables or saturation is present for a long enough duration to enable microorganisms to reduce ferric iron to its ferrous condition after which it leaves the profile.
- **i, e, a –** O horizons must be accompanied by a lower case subscript: either an "i, e, or a" which stand for fibric, hemic, or sapric respectively and denote the state of decomposition of the organic material from least to most decomposed respectively.

- **p –** In the NCRN, A horizons frequently have a "p" subscript next to them which denotes that the A horizon bears visible signs of being plowed at one time in history.
- **r –** This subordinate horizon is used only after the C horizon and represents saprolite or bedrock that is decaying in place.
- **ss –** Stands for "slickensides." This condition occurs in soils with a large amount of shrink/swell clays. When the soil is wet, the prismatic soil peds swell and as the soil dries out, the peds shrink causing them to slide against each other polishing the faces of the prisms and causing them to appear glossy and smooth.
- **t –** Used next to a B horizon denoting an argillic horizon or the accumulation of illuviated silicate clays moved down from the horizons above.
- **u –** Indicates the presence of human-transported materials.
- **w –** Denotes a cambic (or weak) horizon that has not had a lot of time for soil forming processes to occur and thus does not have many distinguishing strong morphological characteristics. The "w" is used with a B master horizon.
- **x –** Indicates the presence of a fragipan (a dense silica-cemented horizon that impedes root growth and water flow) or fragic conditions.

Subsoil – Any soil beneath the A horizon which could include E, B, or C horizons. Subsoil typically connotes B horizon material, however, in the NCRN composite samples, the term represents anything beneath the A horizon.

Texture – The distribution of mineral particles in the fine earth fraction (particles <2 mm in diameter) into three main size classes: 1) sand (2 to 0.05 mm diameter), 2) silt (0.05 to 0.002 mm diameter), 3) clay (<0.002 mm diameter). The relative proportions of sand, silt, and clay determine the soil texture which influences the surface area of the soil medium. Because the surface of soil particles is the site of water and gas adsorption, nutrient exchange for plants, carbon molecule attachment for C sequestration, and many other biogeochemical reactions, soil texture has an outsized effect on most soil processes.

Textural class – Based on the texture (percentage of sand, silt, clay in a soil sample which add up to 100) the soil textural class (e.g., silt loam, sandy loam, sandy clay loam) can be determined by examining the soil textural triangle chart. There are twelve textural classes with a defined percentage of sand, silt, clay.

Transition horizons – Transition horizons contain properties of two master horizons and are denoted by combining the two appropriate capitalized letters (e.g., AB); the dominant horizon is always listed first.

Volumetric water content (θv) – The volume of water in a specific volume of soil (expressed as the percent of a volume of soil occupied by water). Measured using a capacitance probe.

Appendix B

Tables with Summary Statistics for All Physical Data

Table B1. Summary statistics for bulk density (D_b) in parks of the NCRN.

Park	*n*	Bulk Density (D_b)*	stdev (σ)	Std error
ANTI	38	0.87	0.17	0.03
CATO	117	0.49	0.24	0.02
CHOH	187	0.90	0.23	0.02
GWMP	82	0.82	0.23	0.03
HAFE	59	0.75	0.21	0.03
MANA	50	0.96	0.16	0.03
MONO	46	0.83	0.31	0.05
NACE	140	0.83	0.30	0.03
PRWI	425	0.82	0.27	0.01
ROCR	49	0.80	0.19	0.03
WOTR	16	1.01	0.26	0.06

* Db units are in g cm^{-3}

Table B2. Summary statistics for unsaturated infiltration in parks of the NCRN.

Park	*n*	Unsaturated infiltration (cm hr^{-1})	stdev (σ)	Std error
ANTI	39	237	286	46
CATO	103	497	634	62
CHOH	158	326	594	47
GWMP	77	227	172	20
HAFE	32	232	181	32
MANA	49	220	287	41
MONO	51	254	247	35
NACE	143	297	420	35
PRWI	383	388	414	21
ROCR	53	302	355	49
WOTR	16	123	109	27

Table B3. Summary statistics for saturated infiltration in parks of the NCRN.

Park	*n*	Saturated Infiltration (cm hr^{-1})	stdev (σ)	Std error
ANTI	36	79	109	18
CATO	102	266	346	34
CHOH	146	150	352	29
GWMP	67	86	69	8
HAFE	32	91	83	15
MANA	47	77	98	14
MONO	51	101	116	16
NACE	137	152	250	21
PRWI	361	184	183	10
ROCR	51	129	172	24
WOTR	10	69	82	26

Table B4. Summary statistics for volumetric water content (Θ_v) pre-infiltration in parks of the NCRN.

Park	*n*	Volumetric Water (Θ_v) pre-infiltration*	stdev (σ)	Std error
ANTI	31	20.0	12.3	2.2
CATO	99	17.8	13.6	1.4
CHOH	169	22.4	11.3	0.9
GWMP	72	19.8	10.4	1.2
HAFE	53	17.2	9.6	1.3
MANA	54	24.0	10.9	1.5
MONO	49	18.7	10.9	1.6
NACE	139	20.4	11.6	1.0
PRWI	390	16.8	9.5	0.5
ROCR	54	23.5	10.1	1.4
WOTR	15	17.3	7.1	1.8

* Θv units are percent

Table B5. Summary statistics for volumetric water content (Θ_v) post-infiltration in parks of the NCRN.

Park	*n*	Volumetric Water (Θ_v) post-infiltration (%)	stdev (σ)	Std error
ANTI	31	29.6	14.7	2.6
CATO	98	28.4	14.5	1.5
CHOH	161	30.0	9.8	0.8
GWMP	67	27.3	9.9	1.2
HAFE	48	25.7	11.2	1.6
MANA	51	31.5	9.5	1.3
MONO	46	27.1	7.9	1.2
NACE	134	30.6	8.7	0.7
PRWI	383	25.6	9.6	0.5
ROCR	50	28.4	8.0	1.1
WOTR	13	29.3	5.3	1.5

Table B6. Summary statistics for penetration resistance at 5-cm soil depth in parks of the NCRN.

Park	*n*	5 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	33	253	188	33
CATO	113	358	455	43
CHOH	186	365	374	27
GWMP	57	403	316	42
HAFE	54	568	590	80
MANA	43	561	559	85
MONO	48	315	305	44
NACE	106	268	225	22
PRWI	371	469	597	31
ROCR	45	224	222	33
WOTR	16	580	632	158

Table B7. Summary statistics for penetration resistance at 10-cm soil depth in parks of the NCRN.

Park	*n*	10 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	33	535	322	56
CATO	108	651	728	70
CHOH	182	609	575	43
GWMP	57	761	684	91
HAFE	48	1183	1200	173
MANA	43	1288	1192	182
MONO	48	809	614	89
NACE	105	546	578	56
PRWI	371	901	868	45
ROCR	43	488	745	114
WOTR	16	905	609	152

Table B8. Summary statistics for penetration resistance at 15-cm soil depth in parks of the NCRN.

Park	*n*	15 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	32	879	605	107
CATO	95	711	757	78
CHOH	175	823	846	64
GWMP	54	928	817	111
HAFE	40	1371	1271	201
MANA	42	1713	1258	194
MONO	44	1357	1055	159
NACE	104	743	598	59
PRWI	344	1096	922	50
ROCR	41	637	661	103
WOTR	15	1008	558	144

Table B9. Summary statistics for penetration resistance at 20-cm soil depth in parks of the NCRN.

Park	*n*	20 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	31	1008	674	121
CATO	90	805	873	92
CHOH	163	992	954	75
GWMP	47	965	804	117
HAFE	28	996	831	157
MANA	38	1697	1047	170
MONO	38	1721	1247	202
NACE	100	997	814	81
PRWI	328	1298	1020	56
ROCR	39	866	781	125
WOTR	14	1397	625	167

Table B10. Summary statistics for penetration resistance at 25-cm soil depth in parks of the NCRN.

Park	*n*	25 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	28	1142	717	136
CATO	78	916	929	105
CHOH	149	1199	1162	95
GWMP	45	1344	1164	174
HAFE	23	1244	1049	219
MANA	35	1793	1038	175
MONO	30	2089	1092	199
NACE	97	1381	1156	117
PRWI	306	1471	1092	62
ROCR	38	1105	1057	171
WOTR	12	1643	821	237

Table B11. Summary statistics for penetration resistance at 30-cm soil depth in parks of the NCRN.

Park	*n*	30 cm penetration resistance (kPa)	stdev (σ)	Std error
ANTI	26	1681	1732	340
CATO	67	998	1004	123
CHOH	141	1518	1513	127
GWMP	44	1680	1295	195
HAFE	20	1508	1344	301
MANA	34	1958	1081	185
MONO	22	2023	1048	223
NACE	91	1808	1533	161
PRWI	288	1756	1310	77
ROCR	33	1199	1134	197
WOTR	11	1948	1020	308

Table B12. Summary statistics for aggregate stability in parks of the NCRN.

Park	*n*	aggregate stability (1–6)	stdev (σ)	Std error
ANTI	27	5.6	1.0	0.2
CATO	138	5.7	0.8	0.1
CHOH	166	5.6	0.7	0.1
GWMP	72	5.8	0.6	0.1
HAFE	57	5.8	0.6	0.1
MANA	57	5.6	0.7	0.1
MONO	42	5.8	0.6	0.1
NACE	107	5.7	0.7	0.1
PRWI	354	5.9	0.4	0.0
ROCR	42	5.7	0.9	0.1
WOTR	12	6.0	0.0	0.0

Appendix C

Soil Series in the NCRN

Here we present an alphabetical list of the 85 soil series in the NCRN compiled from Web Soil Survey (Web Soil Survey 2019). After each soil series name, we present a short description of the parent material the series is formed from and frequently the landscape position. All description come from the Official Soil Series Descriptions (USDA 2019).

1. Aden: Stream terraces of the Piedmont Plateau. Alluvial materials from the Triassic area. Quartz and siltsone fragments.
2. Airmont: Mountain drainageways and backslopes of the Northern Blue Ridge. Colluvial materials from schist, quartzite, phyllite.
3. Albano: Head of drainage ways. Alluvium over residuum. Residuum is sandstone, shale, siltstone, argillite of Triassic age.
4. Allegheny: Alluvium in variable areas.
5. Appling: Side slopes of the Piedmont Uplands. Very deep soils formed from felsic igneous and metamorphic residuum.
6. Ashlar: Piedmont. Residuum weathered from felsic igneous and metamorphic rocks. Excessively drained.
7. Atkins: Acid alluvium on flooplains.
8. Bagtown series: Colluvial materials on mountain back slopes, footslopes and benches in the Blue Ridge Province.
9. Baile: Piedmont. Alluvium over residuum. Residuum is acid crystalline rocks of mica schist and granitized schist and gneiss.
10. Beltsville: Silty eolian sediments over fluviomarine deposits on the Coastal Plain.
11. Berks: Residuum weathered from shale, siltstone, fine-grained sandstone. The dominant clay minerals are illite, vermiculite and interstratified vermiculite chlorite. Small amounts of kaolinite are present.
12. Bermudian: Recent alluvium from sedimentary rocks (sandstone, shale) on floodplains.
13. Bigpool: Alluvium derived from sedimentary rocks along major rivers.
14. Blocktown: Piedmont, shallow well drained soils formed from metamorphic phyllite and schist.
15. Bourne: Coastal plain upland soils formed in stratified marine and fluvial deposits.
16. Bowmansville: Recent alluvial soils formed from weathered dolerite or basalt. On floodplains. Lots of stratified sand and gravel.
17. Brandywine: Piedmont upland soils formed from residuum from gneiss and related Cambrian and Precambrian rocks often on steep side slopes >15%.
18. Brinklow: Ridges and sideslopes of the Piedmont plateau. Formed from schist and phyllite.

19. Buckhall: Very deep, well drained soils of the Piedmont Plateau formed from weathered gneiss and schist.
20. Carbo: Found in the Ridge & Valley formed from limestone bedrock.
21. Cardiff: Deep, well drained soils of the Piedmont formed from quartzitic slate, phyllite, and other fine-grained rock. Often contain lots of channers.
22. Chillum: Silty eolian materials underlain by marine sediments on the Coastal Plain.
23. Christiana: Clayey fluviomarine sediments on the Coastal Plain.
24. Codorus: Recently deposited alluvial deposits containing medium to large quantities of mica derived from schist, gneiss, phyllite, and other metamorphic rocks.
25. Combs: Mollisols on floodplains and terrace treads formed from alluvium chiefly from colluvial soils that weathered from sandstone, siltstone, shale, and occasionally limestone.
26. Croom: Coastal Plain soils formed from gravelly fluvial deposits. Loamy-skeletal.
27. Dekalb: Soils found on slopes and ridges formed from acid sandstones.
28. Dodon: Coastal Plain soils formed from loamy marine sediments of Miocene age containing diatomaceous earth and very fine sand.
29. Downer: Coastal Plain soils formed from loamy fluviomarine sediments.
30. Downsville: Formed from old alluvium on high stream terraces from sandstone, shale, limestone. These are paleudults.
31. Duffield: Very deep, well drained soils formed from residual limestone bedrock.
32. Dumfries: Very deep soils on narrow ridges and sideslopes formed from feldspathic sandy sediments.
33. Edgemont: Very deep residual soils from quartzitic rocks and schist.
34. Elk: Alluvial mixed parent materials made from mixed sandstone, limestone, shale on stream terraces.
35. Elkton: Low-lying uplands and lowland soils formed from silty eolian material underlain by marine sediments. Poorly drained endoaquults. Ancient floodplains.
36. Elsinboro: Can be on piedmont or coastal plain. Heavy mica throughout the profile. Loamy mica bearing alluvium. Stream terraces.
37. Fairfax: Fluvial materials on the surface over residual schist and gneiss on Piedmont uplands.
38. Fallsington: Coastal Plain Soils formed from fluviomarine sediments.
39. Funkstown: Colluvium and alluvium washed down from surrounding uplands that covers underlaying limestone residuum. These soils occupy upland draws and head slope positions.
40. Glenelg: Soils of the Piedmont and Blue Ridge formed in residuum weathered from micaceous schist.
41. Hagerstown: Deep limestone residuum soils in the valley bottoms of the Ridge & Valley.
42. Hammonton: Coastal Plain Soils formed from fluviomarine sediments.

43. Hatboro: Soils on floodplains formed from alluvium derived from metamorphic schist, gneiss, and other crystalline rocks.
44. Haymarket: Residual soils from diabase and basalt. Triassic rocks.
45. Hazel: Piedmont residual soils on slopes. Sandstone and phyllite.
46. Highfield: Soils on mountain crests, slopes and intermountain valleys. Formed from metamorphosized igneous rocks.
47. Howell: Deep well drained soils in marine sediments with detectable amounts of diatomaceous earth and/or glauconite.
48. Huntington: River valley soils on floodplains. Alluvium from sedimentary rocks.
49. Ingleside: Coastal Plain soils from alluvial and marine sediments.
50. Lenni: Poorly drained depressional soils formed from clayey fluviomarine sediments.
51. Lindside: Floodplain soils formed from calcareous or limestone alluvium.
52. Manassas: Colluvium and residuum in the Piedmont from Shale, Siltstone and conglomerate.
53. Manor: Piedmont soils formed from residual micaceous schist.
54. Mattapex: Soils formed in silty eolian over fluviomarine sediments on the Coastal Plain.
55. Meadowville: "Undulating to rolling uplands of the Piedmont Plateau around the head of drainageways, in saddles or depressions. Formed in acidic and basic rock material washed down from higher slopes."
56. Melvin: Alluvium from shale, sandstone, limestone and sedimentary rocks on floodplains.
57. Monogahela: Old alluvium from acid sandstone and shale on stream terraces and toeslopes.
58. Muikirk: Coastal Plain soils formed in a thin sandy mantle overlying old Cretaceous clays.
59. Myersville: Blue Ridge Mountain soils formed from basic crystalline rocks such as greenstone.
60. Neabsco: Coastal plain soils formed from stratified marine and fluvial sediments
61. Nollville: Formed on convex upland ridges in residuum from limestone and limy shale.
62. Occoquan: Formed on summits, shoulders and sideslopes of narrow ridges in the northern part of the Piedmont Plateau. Underlain by schist and gneiss.
63. Opequon: Limestone uplands on summits, shoulders, backslopes.
64. Orenda: Piedmont residual soils formed from basic metamorphic rocks—hornblende schist and hornblende gneiss.
65. Penn: Red shale, siltstone and sandstone (but non calcareous) soils of uplands.
66. Pope: Alluvium from sandstone, siltstone, shale on floodplains.
67. Potobac: Loamy and sandy fluvial sediments of the Coastal Plain.
68. Purcelville: Residual soils formed from various kinds of schists in the Blue Ridge Uplands.

69. Quantico: Stratified marine and fluvial sediments of the northern coastal plain. Lots of feldspathic sands.
70. Ravenrock: Colluvium from metamorphic metabasalt and metarhyolite on the backslopes and footslopes of the Blue Ridege. Typically rocky.
71. Rhodhiss: Piedmont soils formed from felsic crystalline residuum.
72. Rohrersville: Soils on the lower footslopes in the Blue Ridge and along drainage courses formed in local colluvial and alluvial material over residuum from metabasalt and metaandesite.
73. Ryder: Residuum weathered from thin bedded limestone.
74. Sassafras: Coastal Plain fluviomarine sediment soils.
75. Spriggs: Piedmont soils but weathered from mafic rocks.
76. Stumptown: Colluvium/Residuum from quartzite, muscovite schist, phyliite on ridges and sideslopes of the Blue Ridge.
77. Swanpond: In the limestone valleys, these are formed from very old (from the Cambrian and Ordovician periods) limestone and have vertic properties (even slickensides).
78. Talladega: Soils on the summits and sideslopes of the Blue Ridge and Ridge and Valley regions formed from metamorphic rocks.
79. Thurmont: Formed in metamorphic colluvium on footslopes, colluvial fans, benches and stream terraces in the Blue Ridge.
80. Trego: Formed in alluvial fans and colluvial footslopes out of alluvial metamorphic materials.
81. Weverton: Soils formed from residual or colluvial muscovite schist, phyllite, quartzite in the Blue Ridge.
82. Wist: Coastal Plain soils formed from glauconitic-bearing fluviomarine sediments.
83. Woodstown: Coastal Plain soils formed from sandy marine and old alluvial sediments.
84. Worsham: Soils of the Piedmont formed from alluvium formed from granite, gneiss, schist. Poorly drained soils at the heads of drains and base of slopes.
85. Zion: Soils on the Piedmont uplands (summits, shoulders, backslopes) formed from mafic rocks (hornblende schist, gabbro, diorite, diabase, or dacite).

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