# ASSESSING THE SUITABILITY OF ROTARY CORERS FOR SAMPLING EXCHANGEABLE CATIONS IN ROCKY SOILS

by

Carrie R. Levine

A thesis
submitted in partial fulfillment
of the requirements for the
Master of Science Degree

State University of New York
College of Environmental Science and Forestry
Syracuse, New York
August 2011

Approved: Department of Forest and Natural Resources Management

Ruth D. Yanai, Major Professor

Charles M. Spuches, Chair
Examining Committee

David H. Newman, Department Chair

S. Scott Shannon, Dean
The Graduate School

# Acknowledgements

I would first like to acknowledge the funding sources which allowed me to conduct the research that has contributed to this thesis. This project was funded in part by the Vassar College Environmental Research Institute, the Northern States Research Cooperative, the Edna Bailey Sussman Foundation, and the National Science Foundation's Long-Term Ecological Research network office.

I would like to thank my advisor Dr. Ruth Yanai for her support during the preparation of my thesis, as well as her encouragement of my other various side projects during my time at ESF. Ruth let me explore many different research projects, but was still encouraging when I came back to the original plan in the end. I really appreciate the new direction our research has taken recently, and I'm excited to continue collaborating in the future. Thanks also to my other committee members, Dr. Steven Hamburg and Mr. Matthew Vadeboncoeur, for their helpful comments and guidance on the preparation of this manuscript. Thanks especially to Matt for being my mentor during my summers in New Hampshire. He helped me get acquainted with the study sites and the project, was always willing (and quick) to answer a multitude of questions, and even snuck in some C and N samples to his lab's queue when I was in need. Thanks also to Dr. Eddie Bevilacqua and Dr. Charles Spuches for serving on my examining committee.

There are many people who assisted me with the field and lab work required to complete this project. Thanks to Tyler Refsland, Kikang Bae, and Bali Quintero for assistance with power coring, and especially to Tyler for his patience with me as I fumbled my way through my first field season. Thanks to William O'Neill and Chuck Schirmer for help with soil sieving and laboratory analyses, and thanks especially to Bali Quintero for his invaluable help on the ICP. Thanks to April Melvin and Dr. Christy Goodale at Cornell University, and Dr. Ben Rau and Dr.

Dale Johnson of the University of Nevada for allowing me to use their study sites and unpublished data in my analyses. Thanks especially to April and Ben for their guidance on using the power corer and suggestions for data analysis.

Thanks to all the members of the Yanai lab who have spent various amounts of time over the last two years patiently listening to me try to explain the difference between inner, outer, spoon, and cardboard samples, and for your helpful comments on proposals, posters, presentations, and my thesis. Thanks to Anna Harrison for being my thesis guru and guiding me through all the confusing thesis forms and Word document formats, and for graciously looking at a few too many pictures of Millie during the last few months. Thanks to Stephie, Dan, Kenny, and Shelley for attempting to read my publications (or at least telling me how nice the figures look) and for your encouragement and love. And lastly, thank you to Brendan for helping me learn to enjoy life in Syracuse, for being the world's most agreeable unpaid field technician, for moonlighting as my personal graphic designer, and for everything else.

# Table of Contents

# List of Tables

# List of Figures

# List of Appendices

# Abstract

C.R. Levine. Assessing the suitability of rotary corers for sampling exchangeable cations in rocky soils, 66 pages, 4 tables, 12 figures, 9 appendices, 2011

Ecosystem budgets have been compiled and analyzed with the knowledge that inherent uncertainties exist in natural variability, analytical methods, sampling design, and model selection; however, these uncertainties are rarely propagated through ecosystem budget calculations. Soils are a particularly important area of uncertainty research due to their inherent spatial complexity and the difficulty of accurately sampling soil properties to encompass their variance across space and through the soil profile. A method of soil coring which utilizes a diamond-tipped, motor-driven, rotary corer may increase the expedience of sampling at depth and allow for a sampling scheme that is more representative of spatial variation compared to the use of traditional quantitative soil pits. However, the technique may be limited when attempting to characterize exchangeable cation concentrations of soils due to the grinding action of the corer. We found that soils from cored samples had elevated concentrations of exchangeable cations as compared to quantitative soil pits at sites in Nevada, California, New York, and New Hampshire. We also determined that the contamination in cored samples that is introduced when the corer is inserted and removed during sampling increased estimates of soil mass, exchangeable cations content, %C, and %N. The problem of contamination from inserting and removing the corer was more severe at the NH site, where a deep organic layer was present. Overall, we found that the corer increased concentrations of some cations at all four study sites, though the magnitude of this increase and the specific cations affected differed between sites. We suggest that the rotary corer may not provide precise measurements of soil properties relative to soil pits; however the rotary corer has the advantage of being a quick method for sampling at depth and can more accurately characterize spatial variability with the same effort needed to dig a quantitative pit. Thus, the corer may be appropriate for some study designs, particularly studies that are interested in using this sampling method to assess change over time.

Key Words: Uncertainty, ecosystem, soil, coring, sampling, hardwood forest, Monte Carlo, error analysis

C.R. Levine
Candidate for the degree of Master of Science, August 2011
Ruth D. Yanai
Department of Forest and Natural Resources Management
State University of New York College of Environmental Science and Forestry, Syracuse, New York
Ruth D. Yanai, PhD. ________________________________________

# 1: Introduction

## Introduction to Uncertainty in Ecosystem Studies

The calculation of carbon and nutrient pools and fluxes is an important component of ecosystem studies. Long-term budgets of forests and watersheds have been compiled and analyzed with the knowledge that inherent uncertainties exist in analytical methods, sampling design, and model selection; however, these uncertainties are rarely propagated through ecosystem budget calculations. This seems to be a historical artifact of the limited computational tools available to ecosystem ecologists since the inception of the field, but current computational and modeling capabilities are enabling researchers to pursue advanced methods for quantifying uncertainty in ecosystem studies. Methods of estimating uncertainty in complex systems have progressed greatly in recent years and are a crucial area of research for a broad range of ecological disciplines.

Uncertainty refers to the lack of confidence in a particular estimate. Uncertainty in ecosystem estimates can be classified as resulting from either natural variability or from knowledge uncertainty (Harmon et al. 2007). Natural variability includes heterogeneity in a system either in space or in time, for example the nutrient content of a soil, which is dependent on microsite temperature and moisture regimes as well as differences in soil mass due to varying rock volume (Kulmatiski et al. 2003, Kulmatiski et al. 2004). Natural variability cannot be eliminated from estimates, but its relative contribution to the total error estimate of an ecosystem measurement may be reduced through the utilization of appropriate sampling schemes. Knowledge variability includes parameter and model selection as well as analytic error. Analytic error is estimated during laboratory analysis either by using standard reference materials or through the use of duplicate quality-control samples. Historically, this has been the only source of knowledge uncertainty reported when defining ecosystem measurements that serve as parameters for modeling other ecosystem components (eg. Likens and Bormann 1970). Another important aspect of knowledge uncertainty is the uncertainty associated with choosing a particular model over another. For example, using allometric equations developed specifically for a particular site in New Hampshire led to estimates of aboveground biomass that differed from -3% to +50% from other widely used allometric equations (Fatemi et al. 2011).

The error of an estimate can be represented as a range of values within which the true estimate lies (Harmon et al. 2007). There are both random and systematic errors in ecosystem estimates. Random errors vary in magnitude and direction but average to zero, and systematic error represents a bias in a particular direction. Theoretically, if error is propagated through ecosystem calculations, the error values of each component in the calculation are combined mathematically and reflect the total uncertainty distribution for the calculation. For complex ecosystem measurements, there may be many error terms associated with each pool and flux included in the estimate (Lehrter and Just 2010, Yanai et al. 2010).

Quantifying uncertainty in ecosystem studies is essential for several reasons. First, uncertainty estimates provide a means of assessing how reliable data are and convey the level of confidence we might have in results. Comparisons between point measurements with associated confidence intervals provide a more meaningful comparison of different ecosystems or of a single ecosystem over time. Propagating the uncertainty of different ecosystem components through ecosystem measurements also indicates which sources of error are the greatest contributors to the overall ecosystem error. This has important implications for ecosystem monitoring. Data on natural variation can inform monitoring schemes to maximize the amount of information gained with respect to cost and the amount of time required. Knowledge of both model uncertainty and natural variability can help shape monitoring schemes to achieve the most accurate and precise results. Assessing factors that contribute to natural variability and knowledge uncertainty can lead to better monitoring of ecosystems over time, which has important implications for a wide range of important environmental research topics.

## Quantifying Uncertainty in Soil Measurements

Soils have long presented a problem for quantifying ecosystem budgets. They are notoriously heterogeneous in both in depth and across landscapes (Hamburg 1984, Kulmatiski et al. 2003, Li et al. 2010, Johnson et al. 2011, Boone et al. 1999). They also vary greatly at small scales due to the influences of microclimate regimes, vegetation influence, and the distribution of roots and coarse fragments. For example, Conant et al. (2003) found that the coefficient of variance (standard deviation divided by the mean) of C in forest soils ranged from 60 – 126% in second growth and old growth forests. When detailed information on soil characteristics or processes is required, it necessitates very concentrated sampling to capture this variability. This sampling can be destructive, time-consuming, and labor-intensive.

Historically, soil pools have been described in ecosystem budgets without associated uncertainty (eg. Bormann et al. 1977, Yanai 1992, Likens et al. 1998, Likens et al. 2002, Fahey et al. 2005). Budgets are often constructed using mass-balance constrained estimates for variables, particularly element fluxes, which are not directly measured. For example, uptake of P in mineral soil can be estimated by adding the P transferred from roots in the mineral soil to aboveground biomass, root turnover in mineral soil, and P in root exudation and accumulation in the mineral soil (Yanai 1992). As a result, there are often exact values ascribed to ecosystem processes that may be an artifact of uncertainty in other pools or fluxes that are simply not accounted for in the budget calculations. For example, Bormann et al. (1977) described a missing

N source in the Hubbard Brook Ecosystem budget of 14.2 kg N ha$^{-1}$ yr$^{-1}$, which was described as biological N fixation; however, when N fixation was directly measured in a later study, it was found to be far less than the value predicted by the original N budget (Roskoski 1980). Organic N content of mineral soils is a large amount of the N found in the ecosystem (5900 kg N ha$^{-1}$, SD = 2700; Huntington et al. 1988), with a large minimal detectable change over time that is more than sufficient to account for the budget discrepancy attributed to N fixation (Hamburg et al. *in prep.*) Soils are the largest ecosystem pools of many nutrients and they are almost never sampled sufficiently to allow for a high confidence in soil content measurements.

## Challenges for Soil Monitoring over Time

Accurately quantifying change in soils is an important area of research for many ecological studies. The focal point of this research has been the monitoring of carbon storage in soils due to the importance of soils for sequestering atmospheric carbon. Accurately quantifying rates of belowground C sequestration is a key component in the implementation of effective carbon offset programs. Monitoring change in the content of soil exchangeable cations over time is also an important area of research in soil science due to the evidence that concentrations of some exchangeable cations in forest soils have become depleted in recent years as a result of acid deposition (Yanai et al. 1999, Hawley et al. 2006). Additionally, detecting change in soils as a result of changes in land use such as conversion of agricultural land to forest (Hamburg 1984, Richter et al. 2000) or forest harvest practices (Johnson et al. 1991a, Johnson et al. 1991b) is an important component of managing soil resources (Li et al. 2010, Conant et al. 2003). Long-term research and chronosequence studies have indicated the influence of land use changes on soil nutrient storage (Hamburg 1984, Richter et al. 2007), but due to the heterogeneity of soils both across space and with depth, sampling schemes often do not provide adequate information to accurately characterize soil change over time (Stone 1975).

When monitoring change in soils, it is often the case that soils in a particular location are measured at two time intervals and these time intervals are treated as distinct populations that are then compared statistically (Yanai et al. 2003). The ability to detect a significant change in mass, C, or other nutrients may be low, though it is possible that there is in fact a substantial change. This can be due to the inadequacy of the sampling scheme. For example, Yanai et al. (2003) demonstrate that in a northern hardwood forest, the power to detect a small (10%) change in forest floor is low unless the sample size exceeds 80. The inability to detect a significant change may also be due to the size of a change relative to a total pool. For example, the average C sequestration rate in a North American grassland was two orders of magnitude smaller than the estimated amount of C stored in soils (Conant et al. 2001), making a change in soil C difficult to detect due to the high level of spatial heterogeneity.

Maximizing detectable difference is essential when designing sampling schemes for long-term measurements (Yanai et al. 2003, Conant et al. 2003). The number of samples required to detect a minimum change in a forest ecosystem can be quite high. For example, in an old-growth coniferous forest, Conant et al. (2003) estimated that over 60 composite samples with an area of ~2 $m^2$ and depth of 0.3 m are required to detect a change of 60 Mg C $ha^{-1}$. This is a large sampling effort that is not likely to be undertaken. Additionally, change over time in upper soil horizons is often extrapolated to change in deeper soils due to the relative ease of sampling higher in the soil profile, which adds additional uncertainty to ecosystem estimates. Monitoring of soils can be improved by incorporating a more comprehensive understanding of the many sources of uncertainty.

## Addressing Natural Variability and Knowledge Uncertainty in Soil Measurements

### *Natural Variability*

Inherent natural variability in soils cannot be lessened or eliminated using uncertainty analysis. It is a basic feature of the soil system. Uncertainty analysis can be used to better describe this variability and may also be used to determine sampling schemes that can most effectively decrease the error around estimates of natural variability. Current soils research has been concerned with ways to increase understanding of natural variability of soil nutrients and soil physical characteristics in order to better quantify soil nutrient pools and their change over time.

One approach to better quantifying natural variability in soil systems has been to over-sample a small area to map soil variables at a very small scale to understand the minimum amount of sampling needed to quantify the spatial variability. Researchers have also been using spatial models such as ordinary Kriging and inverse distance weighting within geographic information systems to map spatial variation of soil variables based on sampling at small scales (Li et al. 2010). These two methods could be combined using models that remove a range of information for highly sampled areas to asses the sampling scheme required to achieve an understanding of spatial variability within a certain deviation from the most intensely sampled model. The amount of information required to obtain a sufficiently precise and accurate estimate relative to the most highly-sampled model will depend on the goals of the researchers.

### *Knowledge Uncertainty*

In terms of soil science, knowledge uncertainty refers to the error associated with the models and parameters used to quantify soil variables. There are several factors that contribute to the large model and parameter uncertainties present soil studies. One factor is the range of sampling techniques available. For example, soil sampling techniques to estimate soil characteristics on an area basis include but are not limited to the soil clod, soil core, irregular hole, quantitative soil pit, and sand-cone techniques (Andraski 1991, Lichter and Costello 1994, Hamburg 1984, Page-Dumroese et al. 1999). There are even more techniques included within these categories. For example, a soil pit may be excavated and weighed in the field to directly measure soil mass (Hamburg 1984, Johnson et al. 1991a and b), or it may be excavated without weighing the total mass, and instead the bulk density can be taken from samples along the walls of the pit (Johnson et al. 2005). There have been many studies comparing the sampling bias of alternate soil extraction or excavation techniques (Page-Dumroese et al. 1999, Kulmatiski et al. 2003, Rau et al. 2009, Rau et al. *in press*), and it is also important to compare two techniques when a new technique is developed. Additionally, not every sampling technique is appropriate for each soil type. In fact, there have been many studies that have investigated the best soil extraction or excavation technique for specific soil types, such as studies focused specifically on corers for rocky forest soils (Jurgensen et al. 1977, Harrison et al. 2003, Kulmatiski et al. 2003, Ponder and Alley 1997).

Some knowledge error in soil studies may also result from discrepancies in definitions of soils. Soil studies often do not consider the >2mm fraction when estimating soil C or N (Zaboski et al. 2011), though it has been demonstrated in several studies that this soil fraction may contain large stores of soil C and N that remain unaccounted for under the typical sampling scheme (Ugolini et al. 1996, Corti et al. 1998, Whitney and Zabowski 2004).

An additional factor that leads to knowledge uncertainty is the fact that there are many steps in soil analyses in which it is possible to introduce bias. The soil is extracted, sorted, sieved, ground, subsampled, digested, and analyzed. Each of these steps incorporates a certain amount of error. Additionally, known differences exist between analyzer machines and between individual laboratories. Though these sources of uncertainty are likely to be small relative to sources of natural uncertainty, it is important that they not be entirely disregarded.

## Methods for Soil Sampling: Developing Techniques to Better Quantify Natural Variability and Minimize Knowledge Uncertainty

Researchers are continuing to develop techniques for quantifying C and nutrient stores in soils. In this section, I will discuss two examples of current areas of soil research that have the potential to improve our ability to quantify soil properties, detect soil change over time, and contribute to more effective soil monitoring programs. The first area of research is related to better understanding and quantifying deep soil dynamics, which have historically been ignored in soil research due to the difficulty and expense of collecting representative samples at depth. The second area of research is related to new techniques for quantifying soil characteristics *in situ* in order to resample exactly the same soils over time, which until recently has not been possible. These areas of research also present interesting case studies in which to compare our understanding of knowledge uncertainty and natural variation.

### *Deep soils*

Deep soils remain one of the least-studied components of the terrestrial ecosystem, despite their important contributions to nutrient cycling and storage (Harrison et al. 2011b). Most of the terrestrial ecosystem C is found in deep soil (Harrison et al. 2011a), but about 90% of more than 300 papers included in recent reviews on land-use effects on soils included data from soils sampled to a 30 cm depth or shallower (Post and Kwon 2000, West and Post 2002, Richter and Mobley 2009). Deep soils have significant effects on ecosystem function and productivity (Harrison et al. 2011b), making this area of study important in ecosystem analyses.

Current research in deep soil dynamics has addressed monitoring change over time (Harrison et al. 2011a), assessing contribution to total soil pools (Zabowski et al. 2011), and more accurately quantifying soil content through better estimates of bulk density in deep soils (Johnson et al. 2011, Rau et al. *in press*.) These studies of deep soils are important because they allow researchers to determine how much information is lost when only shallow samples are measured.  For example, Harrison et al. (2011a) found that in soils measured to an 80 cm depth, 27 – 77% of mineral soil C was in soils deeper than 20 cm. Additionally, Johnson et al. (2011) report that the C content of soils deeper than 20 cm ranged from 4 – 79% for soils located throughout the US. These results are quite variable by site, stressing the importance of specific site characteristics in soil pools. Better methods for sampling deep soils can be used to parameterize more accurate models of soil storage in soils.

### *Monitoring Soil* In Situ

The ability to accurately quantify total belowground carbon storage is currently limited by sampling methods (Aichi et al. 2009). A variety of improved methods for soil laboratory analyses have been introduced in recent years, however, there is currently not a well-tested method for nondestructive, *in situ* sampling of soil carbon contents (Wielopolski et al. 2008). There are currently two promising techniques that may allow for the measuring and monitoring of soil characteristics without excavation. The first, inelastic neutron scattering (INS), utilizes spectroscopy to measure characteristic spectra of elements in soils that are emitted as the nuclei in the soil interact with emitted neutrons (Wielopolski et al. 2008). The second, ground-penetrating radar (GPR), is a geophysical tool that has been used to measure soil depth by emitting an electromagnetic wave and measuring the energy reflected back to the surface when these waves reach an obstruction (Sucre et al. 2011).

The INS approach may provide a way to measure soil C and nutrient contents nondestructively. This approach utilizes spectroscopy to analyze gamma radiation released as fast and slow neutrons interact with nuclei in the soil (Wielopolski et al. 2008). As a result, there are no laboratory analyses necessary for determining carbon contents of soils, and soils may be revisited for future analysis of the exact sampling point. The instrumentation can be used to intensively characterize a single 150 cm diameter area, resolving the problem of microsite variability that is inherent in techniques such a soil coring. For example, 225 cores with a diameter of 5 cm would be required to characterize the same area as one INS measurement. In addition, the device can be pulled while measurements are being taken, in order to integrate measurement over a large area. This feature resolves the problem of variable landscape factors such as large boulders, roots, or buried wood, but it is less useful for implementation in forest settings.

Results from a preliminary study of the INS approach in a mature stand in the Bartlett Experimental Forest demonstrated that the natural variability in the soil C content in an area ~16 $m^2$ (plus the variability in the counting geometry of the INS system) was 7.6% of the mean soil content (Wielopolski et al. 2010). These results were promising, but the system must be developed into a portable unit before its use in forest ecosystems is practical. Additionally, the INS measurements depend on the distance between the gamma ray detector and the ground, so a change in the counting geometry of the INS system is an additional source of uncertainty that was not accounted for in this study. This could be a major drawback for measurements taken years apart, as it would be difficult to place the machine in the precise location so that the counting geometry was precisely replicated.

The GPR approach can be utilized by a single operator and used to estimate soil depth, which is an important parameter when determining soil C and nutrient content. Sucre et al. (2011) tested the device in plots in three systems in the southern Appalachian Mountains, and found that depth estimates were consistent between two antennae types, but that GPR estimates of soil mass (measured along a transect) were significantly deeper than estimates obtained using a traditional soil auger technique (measured using 5 independent points within a plot). The ability of the GPR to measure soil depth along a transect is a benefit over the traditional auger because it encompasses greater spatial variability in less time, thus, the report suggests that traditional augers underestimate soil depth (Sucre et al. 2011).

Both the GPR and INS approaches represent significant advances in the study of soil characteristics. Non-destructive sampling is likely the most effective way to approach the study of change over time in soils, as it is possible to measure precisely the same sampling points at different dates. These approaches demonstrate how new technology can be used to increase our understanding of natural variability in soil estimates.

## Contribution of this Study

Like the recently developed soil sampling methods described above, the manuscript that forms the second chapter of my thesis describes a new technique for collecting soil samples at depth. In this paper, I compare cation concentrations and content measured using a diamond-tipped, motor-driven, rotary corer to estimates obtained from neighboring quantitative soil pits. I use data from four soil types at four sites in the US: a Spodosol in NH, an Inceptisol in NY, a Mollisol in NV, and an Alfisol in CA. This technique has been validated by other investigators for estimating soil C and N content at the three latter sites (Rau et al. *in press*), but still requires validation for measuring exchangeable cations in soils. The use of the rotary corer for extracting cation samples is complicated by the likelihood that ground rock is introduced to the sample while coring. This ground rock may elevate exchangeable cation concentrations in cored samples.

As discussed above, it is important to validate new sampling techniques by comparing them to traditional methods. The use of rotary cores to sample soils could be highly beneficial due to the relative ease of sampling at depth as compared to a quantitative pit. This may improve the monitoring of soils over time, as the rotary corer enables researchers to characterize a large area and the minimal disturbance of coring would enable repeat sampling very close to prior sampling sites. Thus, validating the use of rotary cores could improve characterizations of soils, benefitting a wide range of research and management applications.

## 2: Assessing the suitability of rotary corers for sampling cations in rocky soils

### Abstract

Quantitative soil pits have long set the standard for accurate quantitative soil sampling, but they are notoriously labor-intensive and do not capture spatial variability. The use of rotary cores for soil sampling could improve estimates of soil nutrient contents due to the speed and efficiency of obtaining many measurements at depth and over a large area. We assessed whether this method was appropriate for estimating exchangeable cation concentrations in soils. We hypothesized that the grinding of rock and soil that occurs during coring could potentially bias estimates of exchangeable cation concentrations in soils, and we also hypothesized that the introduction of material from the upper soil profiles to the deeper samples during insertion and removal of the corer might bias cation, C, and N estimates in rotary core samples. We compared rotary cores to soil pits in four soil types at four sites in the US: NH (Spodosols), NY (Inceptisols), NV (Mollisols), and CA (Alfisols). We found that some exchangeable cations had significantly higher cation concentrations in soil cores versus the soil pits ($p<0.05$) at each of the four sites, but which exchangeable cations showed this pattern varied from site to site. The elevated exchangeable cation concentrations in the rotary core samples resulted in large overestimates of exchangeable cation contents when expressed on an areal basis. At the NH and NY sites, we collected the soil introduced to the sample during the insertion and removal of the corer. We found that the mass of this contamination relative to the total core mass was significantly greater ($p=0.01$) at the NH sites (9% of core mass) than at NY (2% of core mass), likely due to the presence of a deeper forest floor. We also found that the contaminated "shear zone" of the core was not limited to only the outer portion of the core. In conclusion, the rotary core did not seem to provide satisfactory, unbiased estimates of exchangeable cation

concentrations, using soil pits as a standard. We suggest that the corer may not be the best method for extracting samples for soil chemistry, but may be appropriate for sampling rock volume and soil mass at some sites. Additionally, the information gained from taking multiple cores in an area may provide important spatial information on soil properties relative to a quantitative soil pit.

## Introduction

Accurately quantifying soil carbon and nutrient pools is important for determining site productivity and assessing ecosystem change over time. Soil carbon estimates are used as indicators of fertility in many systems (Johnson et al. 2002). These estimates also inform models of carbon storage in soils, which have influenced carbon sequestration strategies proposed for use as offsets of anthropogenically derived atmospheric carbon dioxide (Conant et al. 2003, Kulmatiski et al 2004). Soil exchangeable cations are also important indicators of nutrient availability and site productivity. Soil macro- and micronutrients are involved in many metabolic processes and thus, the availability of cations in soils is frequently an important determinant of plant health and survival (Juice et al. 2006; Hawley et al. 2006).

Microsite variability and landscape-level heterogeneity present a challenge for site assessments and the estimation of soil nutrient pools and fluxes (Huntington et al. 1988, Grigal et al. 1991, Kulmatiski et al. 2003). Sampling methods for soil nutrients are characterized by large uncertainties as a result of landscape factors such as vegetation or topography that vary horizontally over the soil surface. Additionally, rock and root volume and bulk density may also vary vertically in the soil profile (Boone et al. 1999, Huntington et al. 1988). There have been several studies detailing the effects of sampling effort and design on variability of nutrients in forest soils (Lundell 1987; Carter and Lowe 1986; McBratney and Webster 1983). Sampling in highly variable sites such as forests requires both intensive and extensive sampling procedures to capture soil heterogeneity (Kulmatiski et al. 2003). Imprecise, inaccurate, and inconsistent soil sampling techniques are a major source of uncertainty in the calculation of nutrient budgets.

Traditionally, the gold standard for soil sampling has been the quantitative soil pit, in which soils are volumetrically removed from a pit by depth increment and the total soil mass is weighed in the field before being subsampled for determination of soil properties (Hamburg 1984, Vadeboncoeur et al., in prep.). Quantitative soil pits resolve the rock volume bias associated with soil cores in that soil mass is measured directly, but they are notoriously time-consuming and destructive. Thus, soil cores are the method most often used to estimate soil nutrients. Many core sampling methods have been developed, including punch cores, bucket augers, and drive-type corers that can be operated either by machine or by hand (Boone et al. 1999, Jurgenson et al. 1977, Ponder and Alley 1997). Manually driven soil cores are the most common and accessible method for rocky or remote sites, but are commonly only used to characterize organic and shallow mineral soils and as a result, the nutrient dynamics of deep soils in these sites remain relatively unexplored (Kulmatiski et al. 2003).

A method for taking undisturbed soil cores at depth using a power-driven corer device was first implemented in rocky forest soils using a diamond-bit coring cylinder (Ponder and Alley 1997). This type of corer can cut through large roots and rocks to a depth of 90 cm or more. This technique is very quick compared to the time-consuming work of digging quantitative pits. Rau et al. (2011) report that it was possible to core to a depth of >1 m in 20-45 minutes, though this will depend on the size, composition, and content of the soil coarse fraction. In the same amount of time required to dig one quantitative soil pit, several cores can be distributed through a site to better quantify spatial variability. Recently, Rau et al. (2011) used this method to compare soil, rock mass, and percent carbon and nitrogen in three sites in the US, and found that there were no systematic biases in the measured parameters when core samples were compared to quantitative pits.

The validation of this method for accurately quantifying exchangeable cation concentrations in soils would contribute to knowledge of important soil properties and allow for more accurate monitoring of long-term soil dynamics. However, the grinding of rock during the coring process raised a concern that this method may not be appropriate for estimating cation concentrations in rocky soils, as the samples may include ground rock and soil (
Figure 1). The grinding of rocks and soils during the coring process releases excess cations into the sample and would thus potentially lead to an overestimation of soil cations, though the magnitude of this effect was not known.

Our objective was to assess the use of rotary cores for quantifying exchangeable cation concentrations in soils. To do this, we compared concentrations of major cations from rotary cores and neighboring quantitative pits. We were also interested in determining whether the “shear zone,” where ground particles contaminated the soil sample, would be limited to the edges of the core shaft. We tested this by subsampling the inner portion of the core and comparing this inner subsample to the concentration of the whole core and the pits adjacent quantitative soil pit. Additionally, we hypothesized that the insertion and removal of the corer was adding material to core samples, primarily from the upper soil horizons. We attempted to quantify this contamination and to determine whether the introduction of this material would bias estimates of concentrations of soil exchangeable cations, C, or N relative to neighboring quantitative pits. We applied this coring scheme to sites in NH (Spodosol), NY (Inceptisol), NV (Mollisol), and CA (Alfisol).

## Methods

### *Experimental Areas*

The CA site is located in the Tahoe National Forest in Truckee, CA (Table 1). Soils are fine-loamy, mixed, frigid Inseptisols (Ultic Haploxeralfs; Murphy et al. 2006). Overstory vegetation is predominantly composed of Jeffery pine (*Pinus jeffreyi* Grev. and Balf.) with some white fir (*Abies concolor* (Gord. and Glend.) Lindl. Ex Hildebr.) and understory vegetation includes sagebrush (*Artemesia tridentata* Nutt.), bitterbrush (*Purshia tridentata* DC.), mule's-ears (*Wyethia mollis* A. Gray), green leaf manzanita (*Arctostaphylos patula* Green), and squawcarpet (*Ceanothus prostratus* Benth.; Murphy et al. 2006).

The NV site is located in the Humboldt-Toiyabe National Forest in Nye and Lander counties, NV. Soils are coarse-loamy, mixed, frigid Mollisols (Typic Haploxerolls; Rau et al. 2009). Vegetation is dominated by sagebrush (*Artemisia tridentata* Nutt.) and single leaf pinyon (*Pinus monophylla* Torr. & Frém), with Utah juniper (*Juniperus osteosperma* Torr. Little) and associated grasses and forbs also present (Rau et al. 2009).

The NY site is located near Ithaca, New York. Soils are Inceptisols (Dystrudepts, Fragiaquepts, and Fragiudepts) developed on glacial till derived from bedrock of Devonian shale (Neeley 1965). Dominant tree species included sugar maple (*Acer saccharum* Marsh), red maple (*Acer rubrum* L.), American beech ((*Fagus grandifolia* Ehrh.), and white ash (*Fraxinus americana* L.; Rau et al. 2011).

The NH site is located in the Bartlett Experimental Forest in Bartlett, New Hampshire. Soils are well-drained Spodosols (Haplorthods) developed on glacial till derived from bedrock of Conway granite (Lyons et al. 1997). Mean annual temperature is 5 °C and mean annual precipitation is ~140 cm (Bailey et al. 2003). Forest composition is typical of northern hardwoods, with an overstory dominated by sugar maple (*Acer saccharum* Marsh), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula allegheniensis* Britton). White ash (*Fraxinus americana* L.), white birch (*Betula papyrifera* Marsh) and red maple (*Acer rubrum* L.) are also present. Sites included in this study were C6 and C8. In C6, cores were extracted near soil pits in plots 1, 2, and 3. In C8, cores were extracted near soil pits in plots 1 and 2.

## *Sample collection*

### *Soil Pits*

Soil pits in the CA and NV sites were 0.25 $m^2$ in area (50 cm inside dimension) and soil pits in the NH and NY were 0.5 $m^2$ in area (70.7 cm inside dimension). In CA site, soil pits were excavated in three depth increments (0-20 cm, 20-40 cm, and 40-60 cm). In NV pits were excavated in four depth increments (0-8 cm, 8-23 cm, 23-38 cm, and 38-52 cm). In NY, mineral soil was excavated in 10 cm depth increments to 50 cm. In NH, mineral soil from the B horizon was excavated in layers (0-10 cm, 10-30 cm, 30-50 cm, 50 cm-C horizon) and when the C horizon was encountered, a C 0-25 cm sample was taken regardless of the actual depth of the pit. Forest floors were collected but were not used in this study.

Soils were sieved in the field (to 10 mm in CA and NV and to 12 mm in NY and NH) and weighed. Subsamples were taken back to the lab, weighed, air-dried, and sieved to 2 mm. To calculate soil moisture content, a subsample was dried at 100-105° C for 24 hours or until the sample reached a constant weight. The <2 mm fraction was archived until analysis.

At the CA and NV sites, bulk density of the < 10 mm fraction was calculated by taking a 100 $cm^3$ sample using an impact sampler at each depth increment prior to soil removal. Total pit volume was calculated for each depth increment by adding the estimated > 10 mm rock volume, the < 10 mm soil volume, and > 10 mm root volume (Johnson et al. 2005). At the NY and NH sites, soil mass was directly measured and bulk density calculated by dividing the mass by the average depth increment by the mass of soil removed from the pit and corrected to account for the oven-dried mass ratio (Hamburg 1984, Vadeboncoeur et al, *in prep*.).

*Soil cores in NV and CA*

One soil core was extracted near a corresponding soil pit in depth increments corresponding to the depth increments of pit excavation. Cores were taken with a 7.6 cm internal diameter diamond tipped core device (Diteq$^{TM}$, Lees Summit, MO) mounted on a rotary motor. Each sample increment was extracted before the core was driven to the next depth increment. Cores were bagged individually, brought back to the lab, dried at 100° C for 48 hours, and weighed. Cores were then sieved to 2 mm. We used data from four cores at the CA site and nine cores at the NV site, each corresponding to an individual soil pit.

*Soil Cores in NH and NY: Method for assessing contamination in cores*

We used data from twelve cores at the NH site and six cores at the NY site. Cores were systematically located within 2 m of a soil pit, and two cores were extracted near each pit (at the NH site, one pit had four associated cores rather than two). We disqualified a core location if a surface rock was visible above the organic soil or if we encountered a rock that was larger than the circumference of the corer within the top 30 cm of mineral soil.

We used a 9.5 cm internal diameter diamond tipped core bit (Diteq$^{TM}$, Lees Summit, MO) mounted on a rotary motor (Briggs and Stratton, Milwaukee WI). When coring, we first removed all organic soil from a 15 x 15 cm block above the location of the core. We cored in sequential increments (0-10 cm, 10-30 cm, and 30-50 cm in NH and NY, with additional increments of 50-70 cm, and 70-90 cm in NH). In NY, the core increments corresponded to the increments of the neighboring pits. In NH, the core increments corresponded to the depth increments of the B horizon of the pits, but differed from the pits once the pits reached the C horizon. Due to the difficulty of accurately determining a change in horizon using the cores (core samples are not removed intact), we chose to use sequential depth increments when coring. We cored until we reached 50 cm in NY or 90 cm in NH, or until we reached a rock that obstructed the entire circumference of the core bit.

We used three methods to assess possible contamination sources during the coring process. First, we used a PVC soil corer with a 4 cm inner diameter to extract a sample from the inner portion of the core to compare the inner portion to the outer portion, where we assumed any contamination resulting from ground rock would be present. We refer to this subsample as the “inner” sample, and the rest of the sample as the “outer” sample. The “total” core sample is composed of the inner and outer samples (Figure 2).

To estimate contamination resulting from inserting and removing the power corer, we used two methods. First, to capture the soil introduced when the core bit was reinserted into the cored hole we placed a cardboard disk with the same area as the cored hole at the bottom of the hole, and inserted a 4 cm-thick wooden disk into the shaft of the corer. Any soil introduced into the hole when the core was inserted was captured between the cardboard disk and the wooden disk, and was kept separate from the cored sample. We collected this sample for all depth increments except the 0-10 cm increment, which we assumed had no contamination introduced to the surface of the sample. We refer to this contamination sample as the “insertion” sample. All insertion samples for each core were pooled and used to estimate the potential contamination for the total core.

To capture the contamination introduced to the sample when the corer was removed, we removed any loose material from the bottom of the cored hole, assuming that this was material that would be included in the sample below but was introduced either from the bottom of the previous core or from the sides of the cored hole walls when the corer was removed. We collected this sample for the 0-10 cm, 10-30 cm, and 30-50 cm depth increments. We were unable to reach further than 50 cm deep, so this contamination sample was not collected from the deep soil samples. We refer to this contamination sample as the "removal" sample. All removal samples for each core were pooled in the field and used to estimate the potential contamination for the total core.

### *Sample processing*

Exchangeable cation concentrations in pit and core samples were measured using a neutral salt extraction. The soils from CA and NV were extracted by mixing five grams of air-dry soil with 20 ml of 1 M ammonium acetate. Samples were centrifuged at 2000 rpm for three minutes and filtered through Whatman #54 filter paper three times, and the supernatent was diluted to 100ml. The soils from NH and NY samples were extracted by mixing five grams of soil (<2mm fraction) with 100 mL 1M $NH_4Cl$ on a shaker table for 60 minutes at room temperature. The extractant was filtered through Whatman #42 filter paper.

Samples from CA and NV were analyzed at the USDA ARS soils lab at the University of Nevada, Reno using a Perkin Elmer Atomic absorption/emission spectrophotometer for Na, Mg, K, and Ca. Concentrations of Na, Mg, Al, Si, K, Ca, Mn, Fe, Sr, and Ba were measured on a PerkinElmer Optima 3300DV inductively coupled plasma–optical emission spectrometer (PerkinElmer, Norwalk, CT) at SUNY-ESF in Syracuse, NY using a four-point calibration curve. Oven-dried mass correction conversions were applied to the cation concentrations.

We determined %C and %N for the insertion and removal contamination samples and for the NY and NH sites, and also for all pit and core samples from the NH site. The NH samples were ground using a mixer mill type MM200 (Retsch, Dusseldorf, Germany) Elementar Vario EL III elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) in at Cornell University in Ithaca, NY. Samples from NY were ground using a tungsten-carbide shatterbox and analyzed with a Thermo Electron DeltaPlus XP isotope ratio mass spectrometer (Thermo Fisher Scientific, Waltham, MA) in at the University of New Hampshire in Durham, NH.

### *Data Analysis*

We analyzed soil mass and exchangeable cation concentrations for differences between soil pits and total cores at all four sites using a mixed linear model. The model included repeat measures to account for depth increments of individual cores and an interaction between concentration or mass and depth. The analyses for the NH sites also included a blocking factor for the two stands in which the pits were grouped. Depth and type of sample (core or pit) were treated as fixed effects. Site, stand, and plot were treated as random effects.

For the NH and NY sites, we also analyzed the difference in exchangeable cation concentration between the inner core and total core and between the inner core and the soil pit using the same model described above. We also analyzed the difference between exchangeable cation concentrations (at both sites) and %C and %N (at the NH site) in the inner portion of the core with no contamination included, with only the insertion contamination included, with only the removal contamination included, and with both contamination sources included over the total soil profile. We compared these combinations to each other and to the same combinations using the concentrations from the total core. The model included a blocking factor for stand for the NH site, and treated the type of sample (core with varying contamination combinations or pit) as a fixed effect and stand and plot as random effects. The percent mass of the total core that was contributed from the contamination samples was compared between the NY and NH sites using a two-sample t-test. All analyses were performed in SAS (version 9.2, SAS Institute, Inc., Cary, NC).

## Results

### *Soil mass, rock volume, and exchangeable cation concentration: Pits vs. Core types*

The core samples at the NH site did not show a consistent bias of over- or underestimating soil mass relative to the soil pits. The average absolute difference in soil mass between the pits and cores was high (36%), but the average difference in mass between the NH pits and cores was not significantly different from zero, indicating that though there was not a systematic bias, the cores and pits did differ in their estimates of soil mass (Figure 3). It appears that the cores had a tendency to underestimate mass in the deep samples (30-90 cm) and overestimate mass at the shallower depths (0-30 cm; Depth x Sample Type interaction: p=0.05; Figure 3). We also found that the cores had a tendency to underestimate rock volume relative to the soil pit when rock volume was greater than 10% (Figure 3). We did not find any correlations between rock volume and soil cation concentrations.

The difference in exchangeable cation concentrations between pits and cores was often significant, but was not consistent. Concentration of K in cores was significantly higher than in the pits at all four sites (Table 4; Figure 5). Concentrations of Na were higher in cores at the NV, NY, and NH sites, though Na concentrations were higher in the soil pits than cores at the CA site (Table 4; Figure 6). Concentrations of Ca were higher in cores at the CA site, but higher in the pits at the NV site (Table 4; Figure 7). Concentrations of Mn were higher in cores at the NH site, but higher in pits at the NY site (Table 4; Figure 8). Concentrations of Mg were higher in CA cores (Table 4; Figure 9). At the NH site, Fe (Figure 10) and Si were higher in cores (Figure 11,

Table 2). The elevated cation concentrations in rotary core samples resulted in large overestimates of cation content relative to soil pits when multiplied to an areal basis (Table 3). At the NH site, the %C and %N and the C and N content (g $m^{-2}$) in cores was not significantly different from the pits.

At the NH and NY sites, where we sampled the inner portion of the core, we detected a systematic bias toward higher concentrations of exchangeable cation in the outer portion of the core relative to the inner core, indicating contamination in the suspected shear zone of the core (Table 2). At the NY site, concentrations of exchangeable K, Mg, and Na were greater in the outer portion of the core than the inner (Table 4; Figure 12). At the NH site, exchangeable Na concentrations were significantly greater in the outer portion of the core than the inner (Table 4; Figure 12).

The inner core had fewer elements that exhibited significantly higher concentrations in the cores as compared to the pits, but there still appeared to be a bias towards higher concentrations in the cores. At the NY site, exchangeable Na was higher in both the inner cores and the total cores, and exchangeable K was higher than the pits only in the outer cores. At the NH site, we saw a similar trend: concentrations of exchangeable Na, K, and Mn were greater in the total cores as compared to the pits, but no differences were observed for these exchangeable cations in a comparison between the inner cores and pits. Both the inner and total cores had elevated concentrations of Fe and Si that were of a similar magnitude. The inner and total cores had Fe and Si concentrations that were both greater than the pits.

### *Concentrations of cations, C, and N: Contamination effects in cores at NY and NH*

Concentrations of exchangeable cations, C, and N in the removal and insertion contamination sources were generally similar to the concentrations found in the first 30 cm of mineral soil. Due to the small mass of these contamination sources relative to the total mass of the core and the fact that concentrations were similar to the upper part of the soil profile, concentrations of exchangeable cations, C, and N in the total core were not significantly increased as a result of including the removal and insertion contamination sources (C: p=0.99, N: p=0.98). The mass that the combined contamination samples contributed to the core mass was significantly greater (p=0.01) at the NH sites (9% of core mass) than at NY (2% of core mass). When concentrations were multiplied to an areal basis, the contamination from the insertion and removal samples represented an additional 1500 ± 484 g C $m^{-2}$ and 61 ± 20 g N $m^{-2}$ at the NH sites, and 177 ± 34 g C $m^{-2}$ and 16 ± 3 g N $m^{-2}$ at the NY site.

## Discussion

### *Soil mass and rock volume*

We found that the soil cores at the NH site were not biased towards over- or underestimating soil mass, though we found that the soil core mass was often not consistent with the mass of the neighboring pit. At the other three sites, Rau et al. (2011) found that differences in mass between the pits and cores varied by site. At the CA site, the soil mass of pits and cores agreed, at the NV site, the soil mass was greater only at depth, and at the NY site, the cores systematically overestimated soil mass. The authors suggest that this may be due to the method of soil pit excavation, where the volume of the pit may be overestimated due to an inability to accurately dig vertical pit walls at the NY site, where mass was measured directly and multiplied by the pit volume. However, the soil pits at the NH site were dug following the same protocol as the pits in NY and no systematic bias was observed between pit and core soil mass at this site. There may still be an important effect of the type of pit on the comparison between pits and cores, but the results do not present any consistent evidence of this. Additionally, in the NH site, we cored to 90 cm when possible, whereas at the other sites, cores were extracted only to 50-60 cm depth. The trend we see in the deep soils of cores underestimating soil mass at this site could be explored further in other studies.

Rock volume seems to have been underestimated by the soil cores at the NH site. This result can be reasonably expected at a site such as this, which has large, boulder-sized coarse fragments distributed throughout the soil. If a fragment larger than the area of the corer was encountered, it could not be measured with the corer, and thus it is likely that coarse fraction volume would be underestimated. Additionally, if the soil coarse fraction is composed mainly of large rocks, as is the case at the CA site, the chances of encountering these rocks with the pit are higher than the chance of encountering one with the corer. Both of these effects may lead to the underestimation of soil coarse fraction, and the evidence for this is strong at the NH and CA sites, where the coarse fraction is composed largely of big, granite boulders (Figure 3). At the NY site, where the rock fragments are shale through which the corer can easily pass, there did not appear to be a bias towards underestimating coarse fraction mass (Figure 3).

Accurately quantifying soil mass and rock content is very important when estimating ecosystem nutrient budgets and processes. The results suggest that the biases resulting from use of the power corer are likely to be site-specific, but this study and the Rau et al. (2011) study provide information for certain sites that may be helpful when assessing whether the rotary corer would be a good choice at another site. Additionally, accurately quantifying these soil characteristics has important consequences when determining soil nutrient content on an areal basis. Concentrations of soil nutrients are multiplied by soil mass, and thus a bias in soil mass influences estimates of soil content. In this study, biases towards higher exchangeable concentrations in the cores as compared to the soil pits led to significantly higher content in soils, even for elements that did not have significantly higher concentrations in the cores relative to the soil pit. Our recommendation is that corers may be useful for sampling soil mass and coarse fraction at appropriate sites, but it is possible that the condition at some sites may not be optimal for estimating both mass and volume. For example, estimates of rock mass from cored samples were similar to pits in sites with shale rock, but not in sites with large, heterogeneously distributed granite boulders.

### *Cation Contamination*

It appears that grinding of the soil coarse fraction during the use of a rotary core resulted in elevated cation concentrations of certain elements at all four study sites, but which exchangeable cations showed this pattern varied from site to site. One explanation for the inconsistency of elevated levels of some cations may be related to the size class of minerals that contribute to the contamination of samples from grinding. We did not find any correlations between rock volume and cation concentration in the cores (data not shown), so it is likely that even the grinding of very small particles in the soil resulted in the release of cations. Additionally, we had expected that a greater coarse fraction at depth (Nezat et al. 2007) might lead to an increased effect of contamination from grinding at depth, but we did not observe an interaction with depth and sampling method for any of the elements we tested.

Our hypothesis that cation contamination may be prevented by subsampling from the inner portion of the core was not entirely confirmed at the NY and NH sites, where we tested the technique. It did appear at both sites that the outer cores tended to have higher concentrations of some exchangeable cations than the inner portion of the core. However, the inner portion of the core still exhibited higher concentrations of some exchangeable cations than the soil pit (Table

2), indicating that the contaminated shear zone was not limited to the edges of the core shaft. The spinning of the core may contribute to the mixing of soil inside the corer.

### *Contamination of C and N*

We confirmed our hypothesis that the introduction of material during insertion and removal of the corer result in elevated contents of C and N introduced from material higher in the soil profile. The concentrations in the insertion and removal samples were not significantly different from each other and were similar in concentration to the soil samples from the upper soil horizons. Though there was not a significant difference between %C and %N in the pits and cores, there was a systematic bias towards overestimating C and N content on an areal basis. Interestingly, much more C and N were contained in the contamination samples at the NH site than the NY site. We believe this is a result of differences in the depth of the forest floor at the two sites. The depth of organic soil removed before cores were extracted at the NH site was 8 cm, while at the NY site there was little or no organic soil due to the presence of invasive earthworms (Suarez et al. 2006). Thus the use of the rotary core for estimating soil C and N may be more appropriate at sites with thin organic layers.

### *Recommendations for Use*

It appears that the rotary coring method may not be an appropriate method for sampling soil mass and coarse fraction at all sites. Though this coring method provides a convenient way to sample these soil properties, particularly at depth, we would not recommend that it be used to estimate these soil properties at all sites due to site-specific biases. Additionally, we found that the rotary coring method may not be appropriate for estimating cation concentrations in soils. In the four soil types tested, we observed elevated cation concentrations relative to soil pits, indicating that this effect of grinding while coring may impact cores in a variety of other systems. The elevated cation concentrations in the soil cores resulted in large biases in content when multiplied to an areal basis. Additionally, though the method of removing the inner portion of the soil core improved estimates of cations relative to soil pit concentrations, we would not recommend using this method, as it appears that this sample was also contaminated, though less severely so.

The use of rotary cores for sampling soil properties has many apparent advantages relative to the excavation of quantitative soil pits. The corer is portable and weighs less than the combined equipment needed for excavating quantitative pits. Coring also requires significantly less time to reach deep soils relative to soil pits (Rau et al. 2011), and has the ability to provide a more extensive quantification of site variability as compared to quantitative pits. This is an advantage in spatially heterogeneous sites such as forests. In some cases, the advantage gained in characterizing spatial variability with the rotary corer may be greater than the difference between pits and cores.

Use of the rotary soil corer for sampling has previously been verified for sampling root biomass in a shrub ecosystem (Rau et al. 2009) and for sampling soil mass, coarse fragment mass, %C, and %N at the CA, NV, and NY sites represented in this study (Rau et al. 2011). We were able to confirm the results for C and N at our NH site, where we did not find a significant difference in soil C and N content between pits and cores, though we did observe a bias towards systematically overestimating soil C, N and exchangeable cation content as a result of the material introduced to the sample during the insertion and removal of coring, relative to the soil cores when the contamination was not included in the total estimate.

The bias towards overestimating soil nutrient concentration and content and underestimating rock volume in a variety of sites is an important consideration for some types of research, such as research to determine nutrient budgets across a landscape or research assessing changes in nutrient pools over time. The corer can be a useful tool for measuring soil physical properties such as soil mass and rock volume at particular sites, but this is dependent on site characteristics such as the size, distribution, and composition of rocks. Additionally, it appears from this research as well as previous studies that cored samples contain concentrations of C and N that are not significantly different to soil pits, but that sites with deep organic soil may be more prone to higher levels of contamination. The rotary cores do not appear to provide consistently accurate measurements of soil exchangeable cations relative to soil pits, but the advantage of characterizing spatial variability may be more important than accurately matching concentrations found in quantitative soil pits, particularly if the objective of a study is change over time rather than quantification of soil chemical properties.

# 3. Summary

The paper presented above describes a contribution to the continuing search for a quick, simple, and accurate approach to measuring soil characteristics. Unfortunately, we found that this method may not provide accurate estimates of soil properties relative to soil pits. We found that site-specific soil characteristics such as rock distribution and size and the depth of the organic layer may be a determining factor in whether or not the soil corer is appropriate for measuring soil physical characteristics such as soil mass and rock volume. Additionally, we observed a bias towards overestimating C and N content contained in the contamination that enters the cored samples during the coring process. In terms of exchangeable cation concentrations, we found evidence of elevated concentrations of some elements in the soil cores at all sites, indicating that there is a systematic bias when the rotary corer is used for this purpose. Thus, the usefulness of the corer for measuring soil chemistry may be limited.

It is not yet clear how the power corer could be best utilized to provide estimates of soil characteristics that are equivalent to quantitative soil pits. One possibility would be to use the corer to more easily reach deep soils, and then to use a different technique to measure nutrient concentrations. It is not clear whether this would be an improvement over qualitative soil pits, nor is it clear how a core might be taken within the small, deep hole left by the rotary core. This may be another avenue for future research efforts.

Accurately quantifying soil properties is a challenge for researchers in a variety of disciplines. In addition to quantifying pools and fluxes, it is crucial to include the uncertainty around estimates in order to assess the confidence around ecosystem predictions. Future research in uncertainty in soil estimates will likely be focused on acquiring a more thorough understanding of spatial variability and variability with depth in the soil profile. In order to better quantify this, new techniques that allow for quick, representative sampling across the landscape and at depth is required. Rotary cores may not be the answer to these problems at all sites, but it seems that they may be useful in appropriate conditions. An important aspect of this area of study is determining the most appropriate and useful methods for soils research at specific sites.

# 4. Tables

Table 1. description of sampling locations included in this study.

| Site | Latitude | Longitude | Elevation (m a.s.l) | Average annual temperature (°C) | Average annual precipitation (cm) | Soil Sub-Order | Parent Material |
|---|---|---|---|---|---|---|---|
| Tahoe National Forest, CA | 39° 15’ N | 120° 49’ W | 1760 | 6 | 70 | Haploxeralfs | Granite |
| Humboldt-Toiyabe National Forest, NV | 39° 15’ N | 117° 35’ W | 2210 - 2230 | 8.5 | 20 | Haploxerolls | |
| Tompkins County, NY | 42° 27’ N | 76° 27’ W | 290 | 7.7 | 90 | Dystrudepts, Fragiaquepts, and Fragiudepts | Shale |
| Bartlett Experimental Forest, NH | 44° 03’N | 71° 17’W | 330 - 460 | 5 | 140 | Haplorthods | Granite |

Table 2. Concentration (μg $g^{-1}$) of exchangeable cations and Si (contained in $H_2SiO_4$) in pit and core soil samples. Inner concentrations are derived from the center subsample of the whole core, and whole core samples are a weighted average of the inner and outer core samples. Numbers are weighted means of profile totals. Standard errors are shown in parentheses.

| | | | | **Major base cations** | | | | **Minor base cations** | | **Multiple complexes** | **Redox-variable** | | **Multiprotic acid anion** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Stand** | **Core Type** | ***n*** | **$Na^+$** | **$K^+$** | **$Mg^{2+}$** | **$Ca^{2+}$** | **$Sr^{2+}$** | **$Ba^{2+}$** | **Al** | **$Fe^{2+}$** | **$Mn^{2+}$** | **$H_2SiO_4^{2-}$** |
| NY | | Inner core | 6 | 12 (1) | 65 (6) | 46 (7) | 260 (20) | 1.2 (0.1) | 44 (3) | 320 (10) | 4 (1) | 41 (11) | 22 (4) |
| | | Whole core | 6 | 16 (2) | 91 (3) | 58 (5) | 330 (40) | 1.6 (0.2) | 47 (4) | 310 (10) | 7 (2) | 36 (5) | 34 (9) |
| | | Pit | 3 | 9 (2) | 150 (70) | 91 (30) | 510 (100) | 2.3 (0.7) | 120 (40) | 600 (160) | 11 (4) | 170 (87) | 41 (10) |
| NH | C6 | Inner core | 6 | 13 (2) | 25 (5) | 7 (1) | 76 (13) | 0.4 (0.07) | 7 (1) | 180 (30) | 16 (4) | 3 (1) | 24 (4) |
| | | Whole core | 6 | 18 (4) | 35 (6) | 10 (1) | 84 (18) | 0.6 (0.2) | 7 (1) | 170 (20) | 20 (2) | 4.0 (1) | 44 (10) |
| | | Pit | 3 | 25 (2) | 44 (20) | 14 (6) | 97 (40) | 0.49 (0.2) | 13 (7) | 320 (200) | 15 (7) | 3 (0.1) | 34 (2) |
| | C8 | Inner core | 6 | 13 (1) | 35 (8) | 9 (1) | 110 (8) | 0.9 (0.1) | 5 (1) | 120 (30) | 17 (4) | 7 (3) | 13 (2) |
| | | Whole core | 6 | 18 (4) | 40 (6) | 11 (1) | 110 (7) | 1.0 (0.1) | 5 (1) | 120 (30) | 22 (5) | 8 (2) | 12 (3) |
| | | Pit | 2 | 18 (0.4) | 30 (0.2) | 19 (1) | 160 (60) | 1.5 (0.8) | 7.5 (3) | 70 (10) | 5.0 (0.05) | 5.3 (3) | 14 (3) |
| CA | | Core | 4 | 1.3 (0.2) | 26 (2) | 54 (6) | 210 (17) | | | | | | |
| | | Pit | 4 | 1.6 (0.1) | 2 (0.6) | 26 (1) | 140 (8) | | | | | | |
| NV | | Core | 9 | 26 (3) | 200 (18) | 14 (0.6) | 130 (4) | | | | | | |
| | | Pit | 9 | 21 (1) | 120 (25) | 14 (0.8) | 150 (4) | | | | | | |

Table 3. Content (g m$^{-2}$) of exchangeable cations in pit and core soil samples. Inner concentrations are derived from the center subsample of the whole core and applied to the total mass of the core, and whole core concentrations are a weighted average of the inner and outer core samples applied to the total mass of the core. Numbers are a weighted average of the total profile. Standard errors are shown in parentheses.

| | | | | | **Major base cations** | | | | **Minor base cations** | | **Multiple complexes** | **Redox-variable** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Stand** | **Final Depth (cm)** | **Core Type** | ***n*** | **$Na^+$** | **$K^+$** | **$Mg^{2+}$** | **$Ca^{2+}$** | **$Sr^{2+}$** | **$Ba^{2+}$** | **Al** | **$Fe^{2+}$** | **$Mn^{2+}$** |
| NY | | 50 | Inner core | 6 | 9.1 (1.3) | 49.1 (4.8) | 35.4 (5.7) | 194.4 (18.6) | 0.9 (0.1) | 33.1 (2.4) | 245.1 (10.4) | 3.1 (0.6) | 31.3 (8.7) |
| | | 50 | Whole core | 6 | 12.0 (1.6) | 68.7 (3.1) | 44.3 (4.5) | 251.2 (30.6) | 1.2 (0.2) | 35.4 (3.0) | 231.6 (8.9) | 5.6 (1.7) | 27.5 (3.9) |
| | | 50 | Pit | 3 | 2.5 (0.3) | 37.6 (8.8) | 24.4 (4.4) | 135.9 (12.2) | 0.6 (0.07) | 34.1 (10.8) | 163.5 (11.1) | 3.0 (1.4) | 41.1 (13.6) |
| NH | C6 | 90 | Inner core | 6 | 9.6 (1.6) | 21.1 (3.0) | 6.2 (0.4) | 89.7 (36.2) | 0.7 (0.4) | 6.1 (1.1) | 135.7 (18.2) | 12.7 (2.2) | 6.2 (4.7) |
| | | 90 | Whole core | 6 | 13.8 (2.8) | 27.3 (4.5) | 7.9 (1.1) | 59.2 (10.9) | 0.4 (0.08) | 5.4 (1.0) | 137.8 (14.2) | 17.2 (2.2) | 2.9 (0.7) |
| | | 100 | Pit | 3 | 8.0 (0.9) | 18.0 (0.8) | 5.6 (0.3) | 39.1 (4.6) | 0.2 (0.07) | 4.6 (0.7) | 120.7 (20.8) | 6.4 (0.8) | 1.5 (0.6) |
| | C8 | 90 | Inner core | 6 | 10.6 (2.1) | 29.1 (8.0) | 7.0 (0.7) | 86.5 (10.0) | 0.8 (0.2) | 3.9 (0.9) | 87.9 (15.1) | 12.5 (2.7) | 5.8 (2.7) |
| | | 90 | Whole core | 6 | 15.2 (4.1) | 32.3 (7.3) | 9.2 (1.0) | 92.7 (9.4) | 0.8 (0.2) | 4.2 (1.1) | 87.4 (15.8) | 16.0 (2.8) | 6.6 (2.4) |
| | | 94 | Pit | 2 | 11.6 (1.7) | 19.7 (2.3) | 12.4 (2.3) | 99.4 (24.4) | 0.9 (0.4) | 4.7 (1.4) | 46.1 (14.1) | 3.3 (0.4) | 3.2 (1.6) |
| CA | | 60 | Core | 4 | 0.53 (0.086) | 10.6 (0.88) | 22.0 (3.2) | 86.2 (10.1) | | | | | |
| | | 60 | Pit | 4 | 0.58 (0.034) | 0.57 (0.080) | 9.4 (0.48) | 48.5 (3.3) | | | | | |
| NV | | 52 | Core | 9 | 8.2 (1.3) | 63.6 (8.1) | 4.2 (0.19) | 43.1 (2.5) | | | | | |
| | | 52 | Pit | 9 | 6.6 (0.66) | 39.0 (8.4) | 4.3 (0.28) | 46.3 (2.6) | | | | | |

Table 4. Average ratio of exchangeable cation and Si (contained in $H_2SiO_4$) concentrations in pit and core soil samples. Inner concentrations are derived from the center subsample of the whole core, and whole core samples are a weighted average of the inner and outer core samples. Numbers are weighted means of profile totals. Significance levels for the CA and NV sites are indicated with asterisks at the following levels: * $p<0.05$, ** $p<0.01$, *** $p<0.001$, ****$p<0.0001$. Significance levels for the NY and NH sites are indicated with plus signs. The significance levels were corrected for multiple tests, and are at the following levels: + $p<0.017$, ++ $p<0.001$, +++ $p<0.0001$.

| | | | **Major base cations** | | | | **Minor base cations** | | **Multiple complexes** | **Redox-variable** | | **Multiprotic acid anion** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **Ratio** | ***n*** | **$Na^+$** | **$K^+$** | **$Mg^{2+}$** | **$Ca^{2+}$** | **$Sr^{2+}$** | **$Ba^{2+}$** | **Al** | **$Fe^{2+}$** | **$Mn^{2+}$** | **$H_2SiO_4^{2-}$** |
| NY | Core : Pit | 6 | $1.8:1^{++}$ | $0.7:1^{+}$ | 0.6:1 | 0.7:1 | 0.7:1 | 0.4:1 | 0.5:1 | 0.7:1 | $0.2:1^{+}$ | 0.8:1 |
| | Inner Core : Pit | 6 | $1.6:1^{+++}$ | 0.4:1 | 0.5:1 | 0.5:1 | 0.5:1 | 0.4:1 | 0.5:1 | 0.4:1 | $0.2:1^{+}$ | 0.5:1 |
| NH | Core : Pit | 12 | 0.9:1 | 1.1:1 | 0.7:1 | 0.8:1 | 0.9:1 | 0.6:1 | 1.1:1 | $2.9:1^{+}$ | 1.4:1 | $1.1:1^{+}$ |
| | Inner Core : Pit | 12 | 0.7:1 | 0.9:1 | 0.5:1 | 1.1:1 | 0.7:1 | 0.6:1 | 1.1:1 | $2.3:1^{+}$ | 1.4:1 | $1.2:1^{+}$ |
| CA | Core : Pit | 4 | 0.8:1* | 13.0:1**** | 2.0:1** | 1.5:1** | | | | | | |
| NV | Core : Pit | 9 | 1.2:1**** | 1.7:1* | 1.0:1 | 0.9:1* | | | | | | |

## 5. Figures

Figure 1. An example of a rock that has been sheared by the rotary corer during coring. The right side of the rock was found in the cored sample and the left side of the rock remained in the wall of the cored hole. The rock broke off before it was shorn completely through; this is visible in the photograph in the upper half of the space between the two sides.

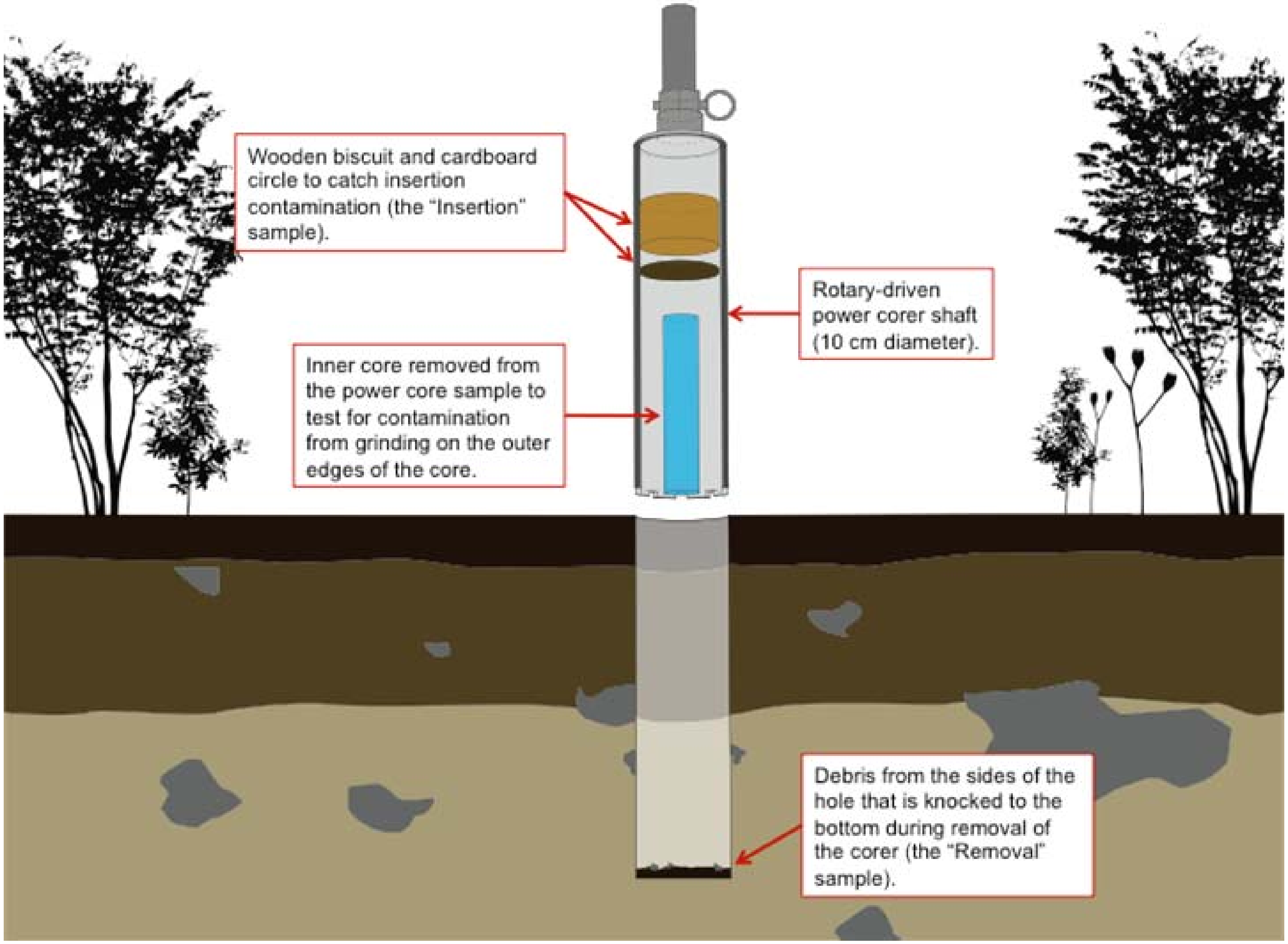


Figure 2. Coring scheme used to collect soil cores at the NY and NH sites.

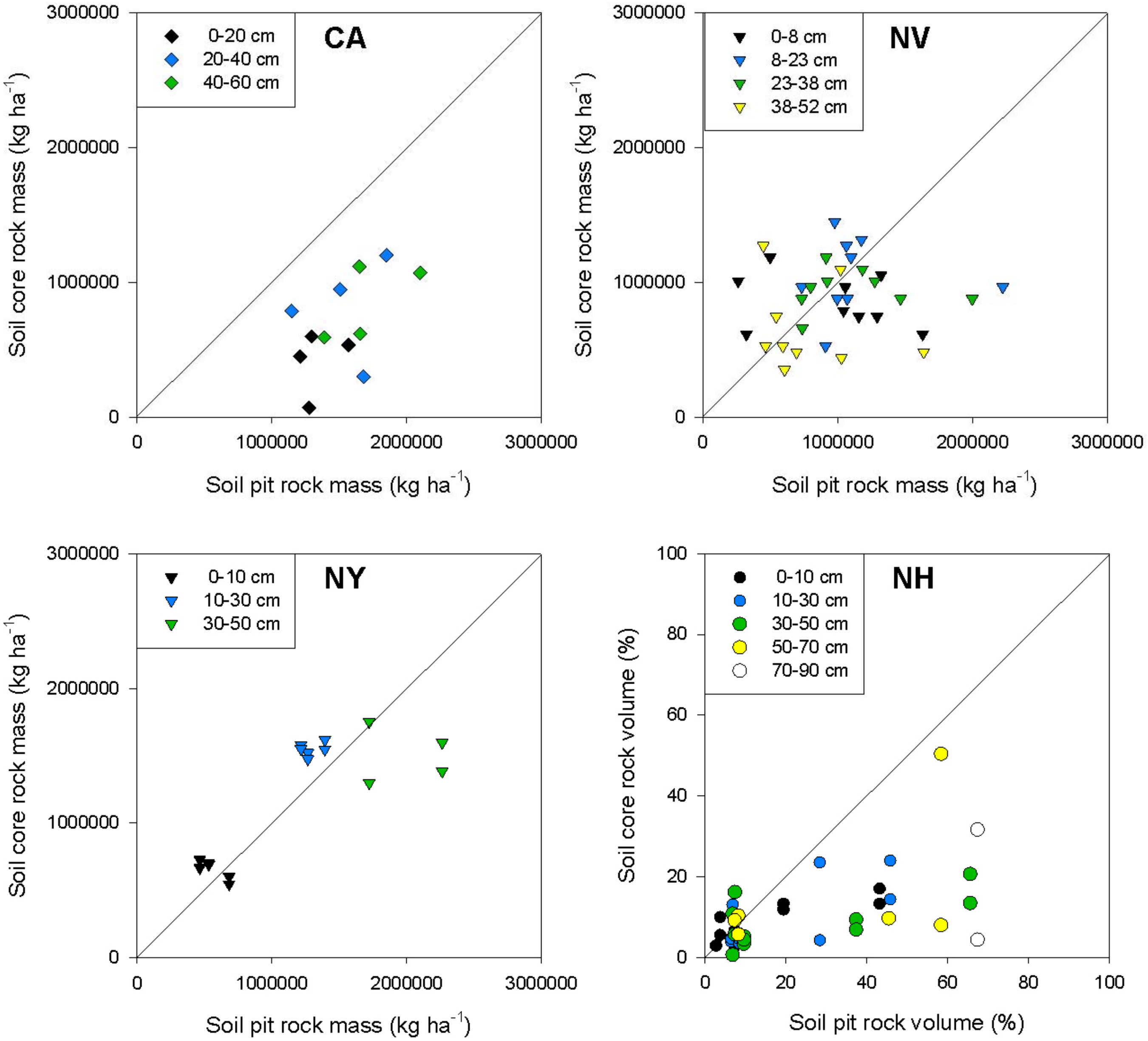


Figure 3. Soil pit and core rock mass (kg ha$^{-1}$) at the four sites. The line represents a 1:1 relationship.

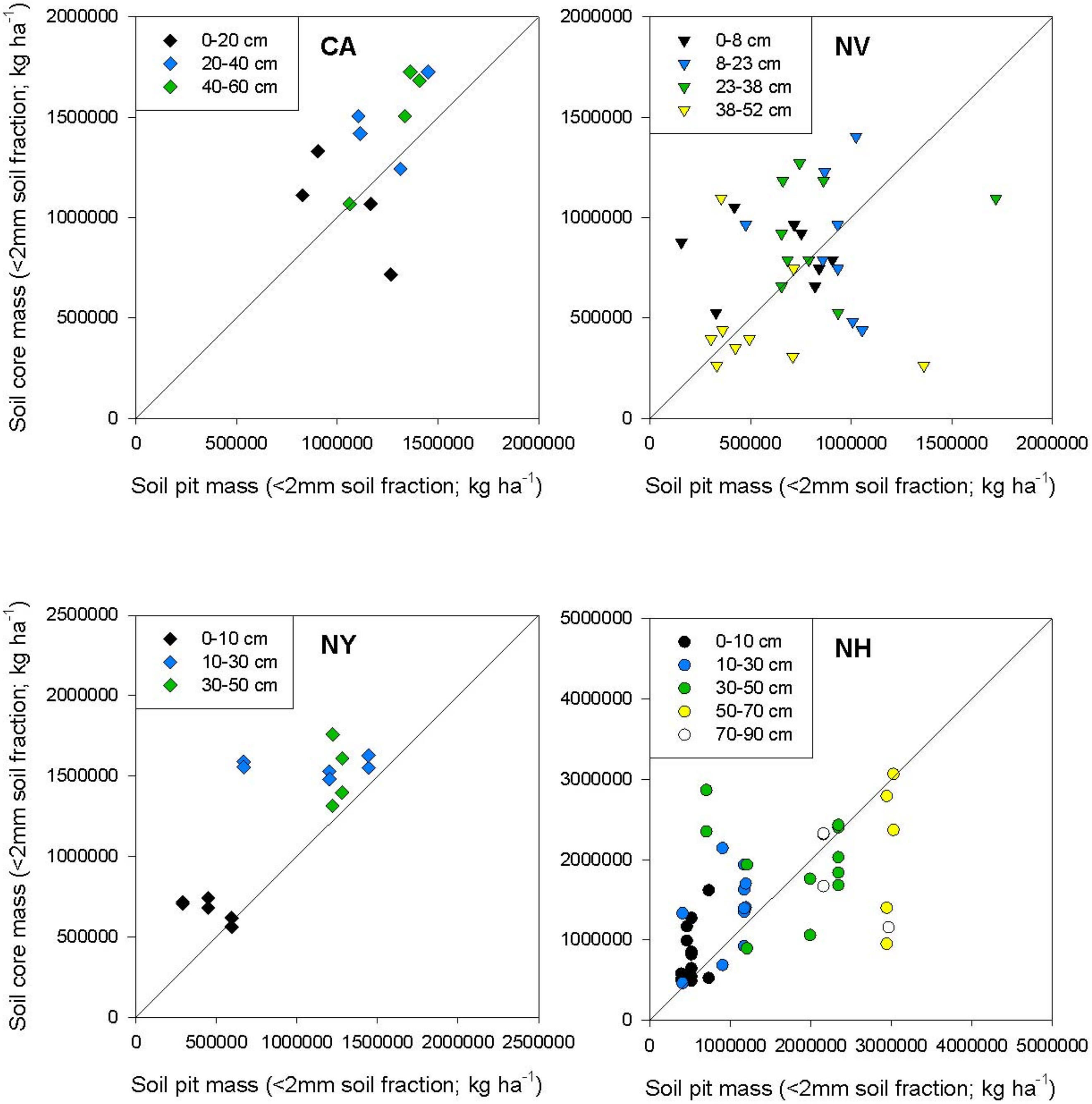


Figure 4. Soil pit and core soil mass (kg ha$^{-1}$) at the four sites. The line represents a 1:1 relationship.

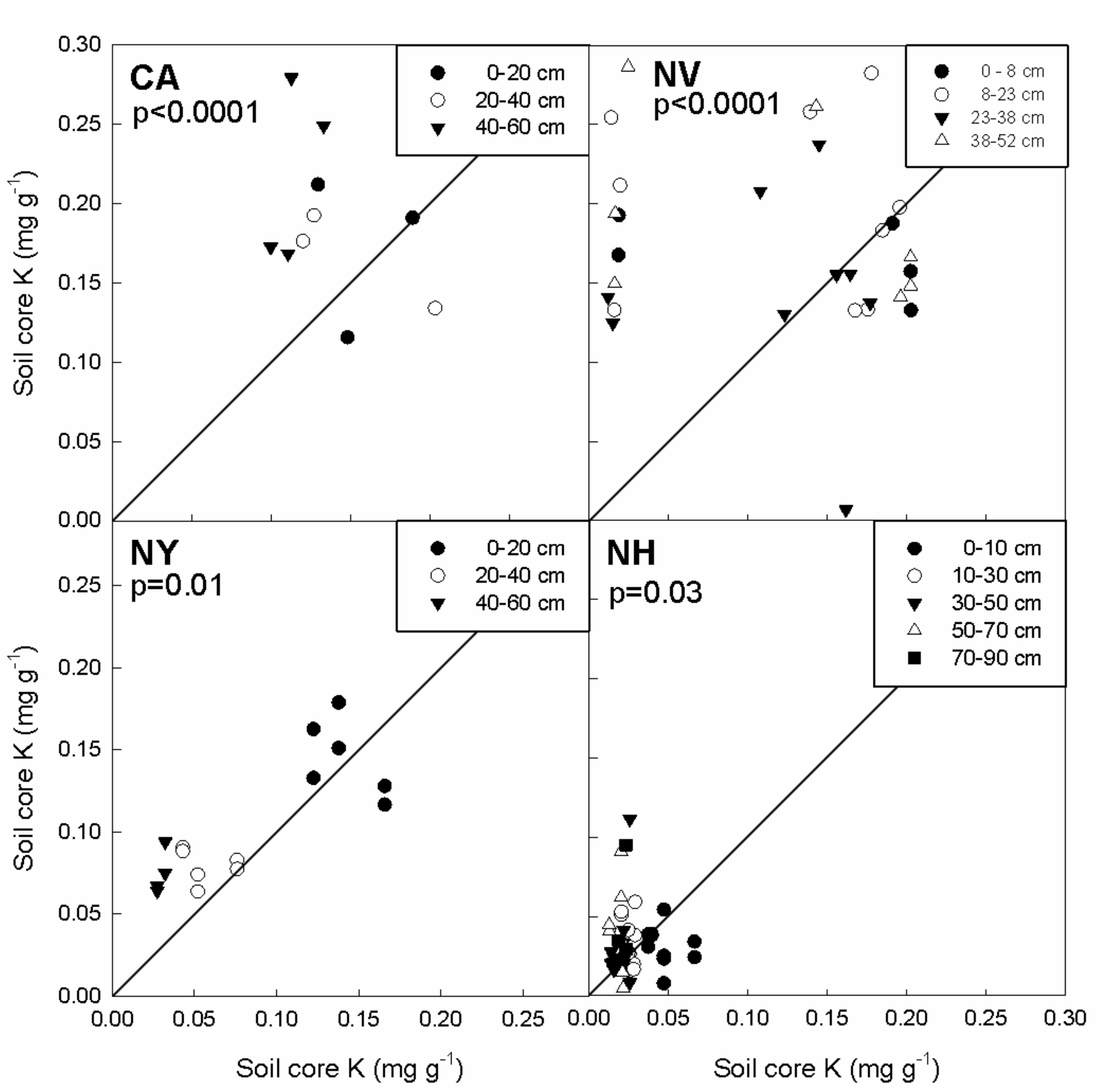


Figure 5. Soil pit K concentrations (mg $g^{-1}$) plotted against soil core K concentrations at the four study sites. The lines represent a 1:1 relationship.

\

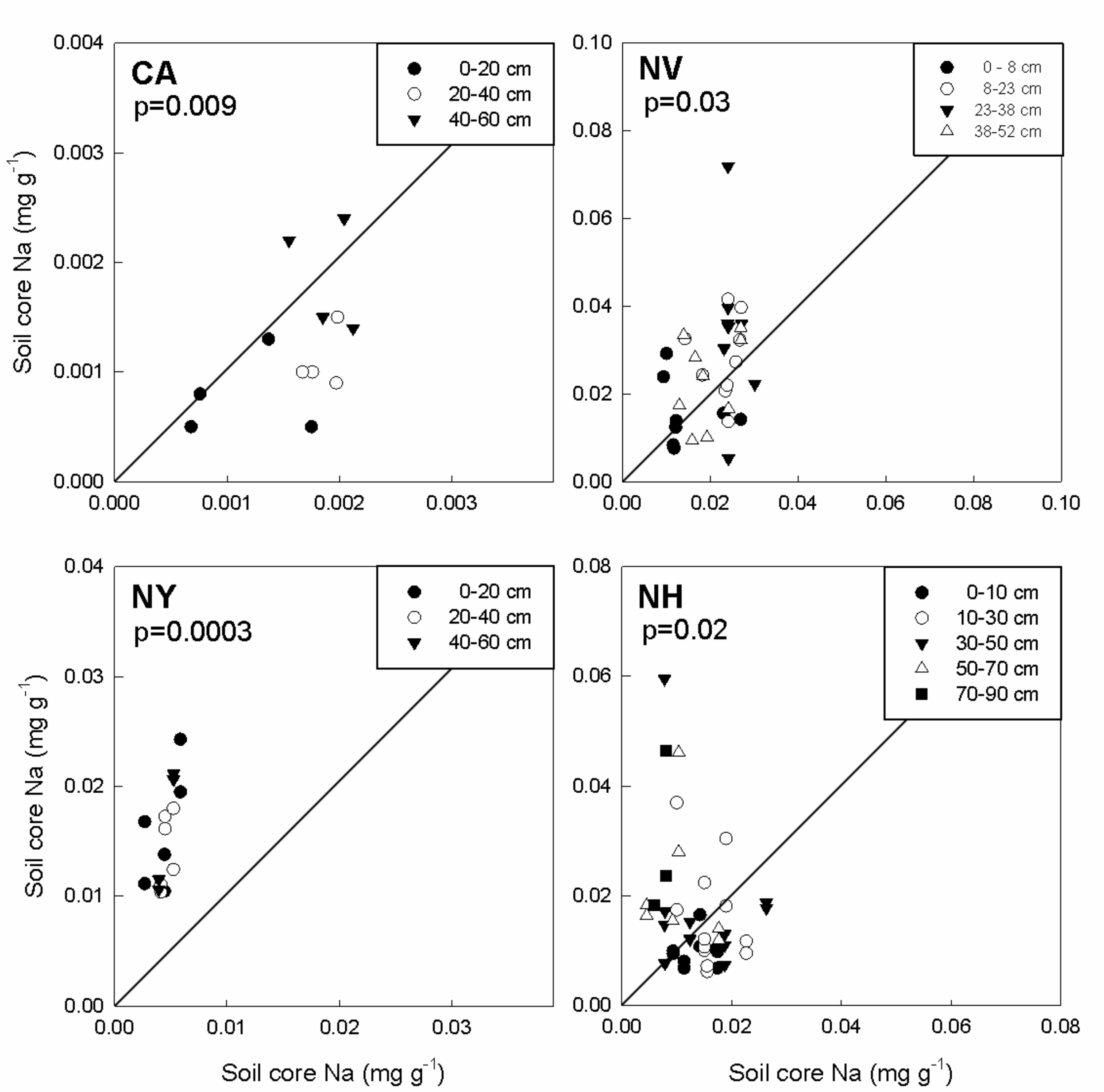


Figure 6. Soil pit Na concentrations (mg g$^{-1}$) plotted against soil core Na concentrations at the four study sites. The lines represent a 1:1 relationship.

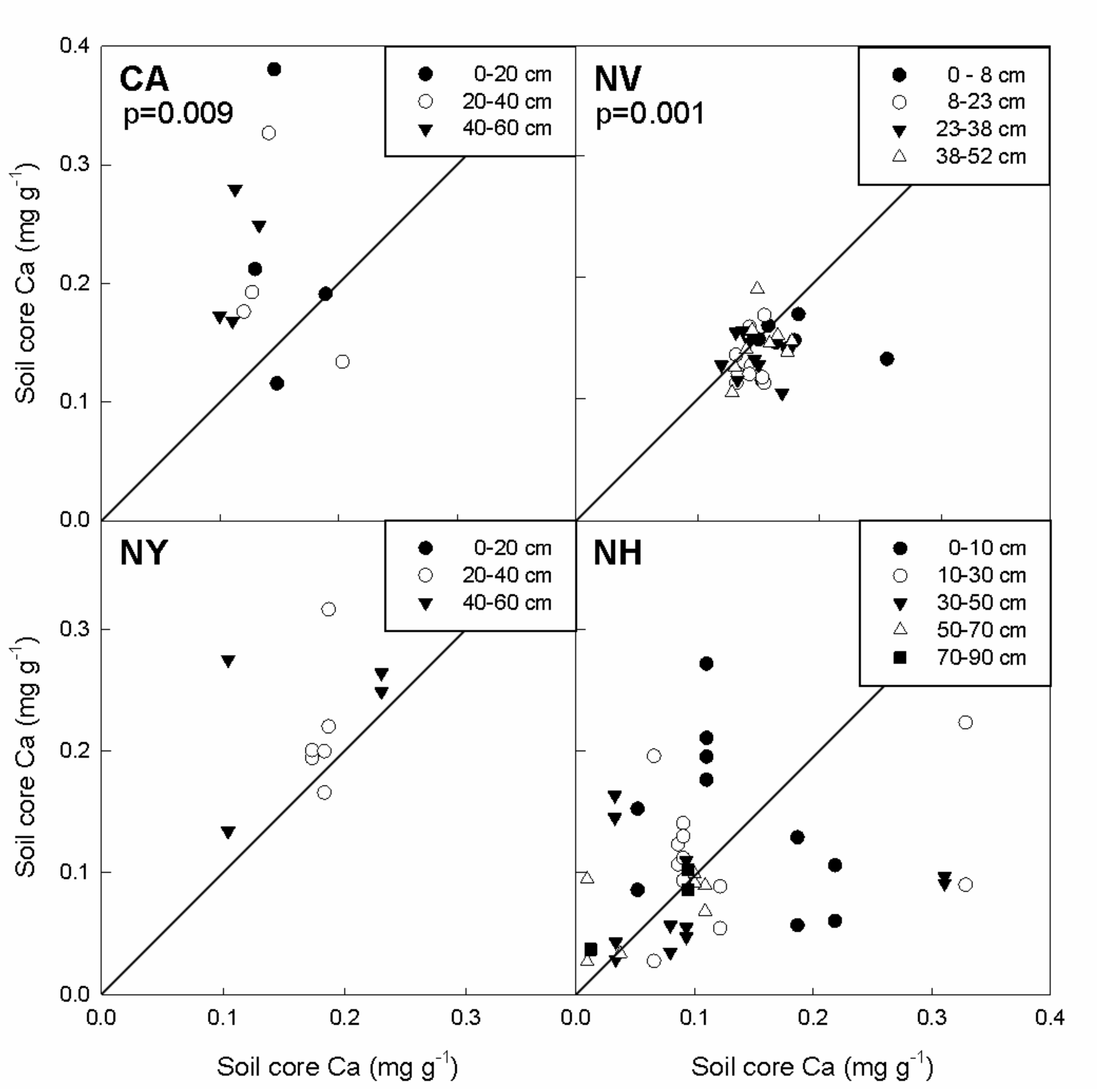


Figure 7. Soil pit Ca concentrations (mg g$^{-1}$) plotted against soil core Ca concentrations at the four study sites. The lines represent a 1:1 relationship.

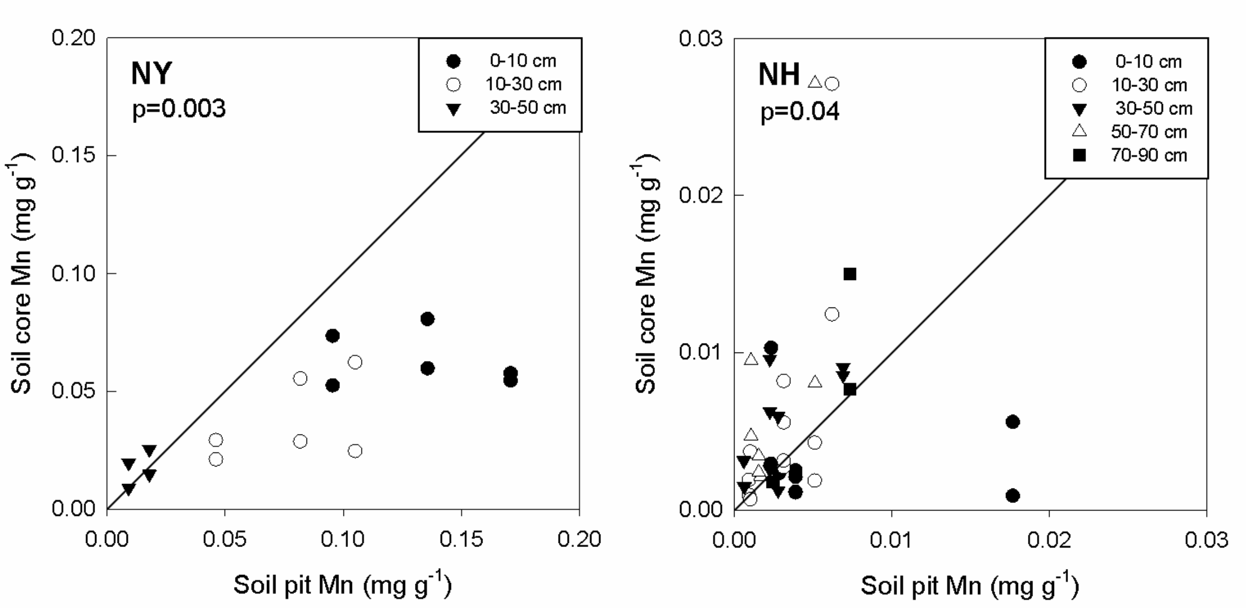


Figure 8. Soil pit Mn concentrations (mg $g^{-1}$) plotted against soil core Mn concentrations at the NY and NH study sites. The lines represent a 1:1 relationship. This element was not analyzed for the CA and NV sites.

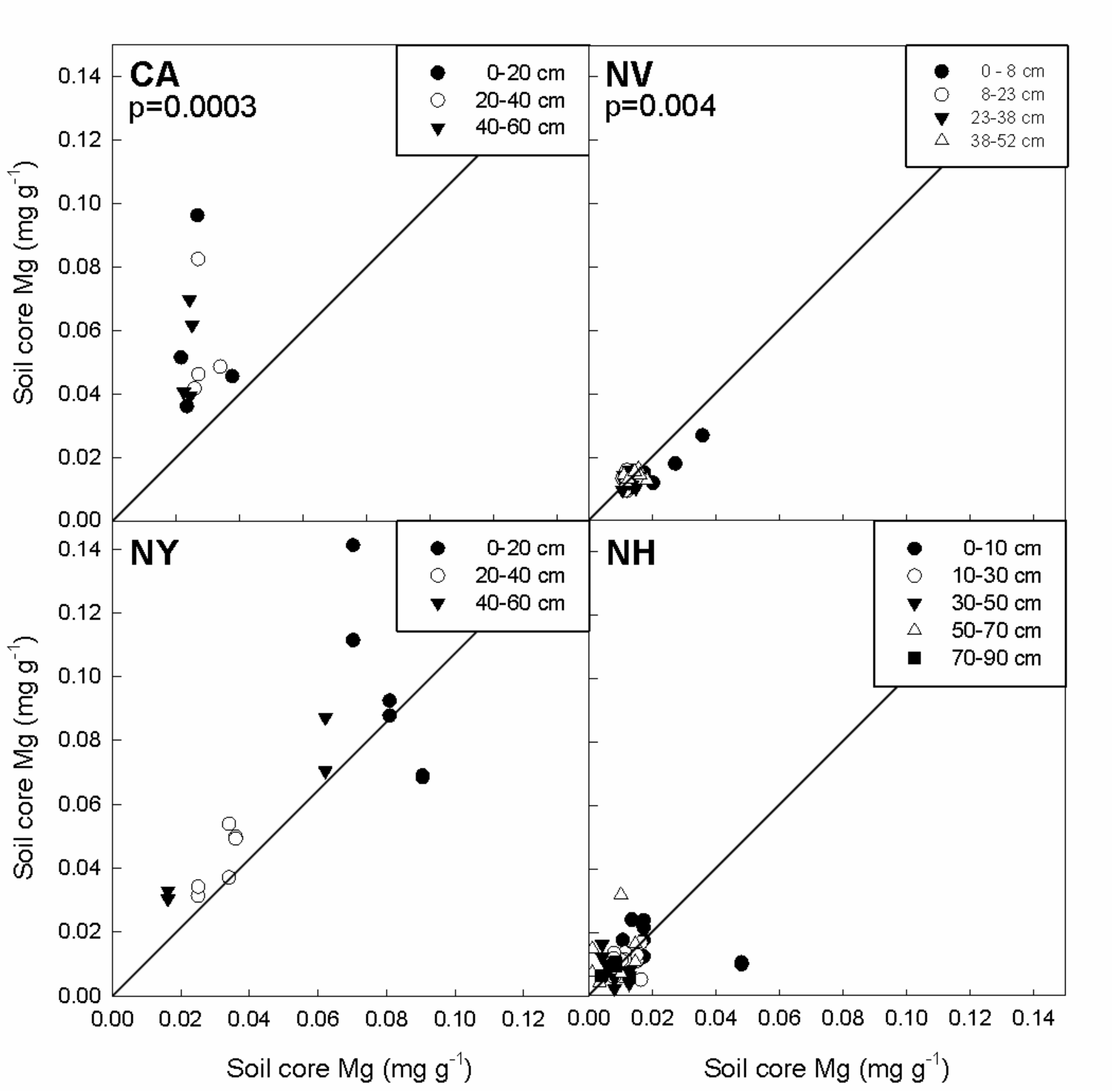


Figure 9. Soil pit Mg concentrations (mg $g^{-1}$) plotted against soil core Mg concentrations at the four study sites. The lines represent a 1:1 relationship.

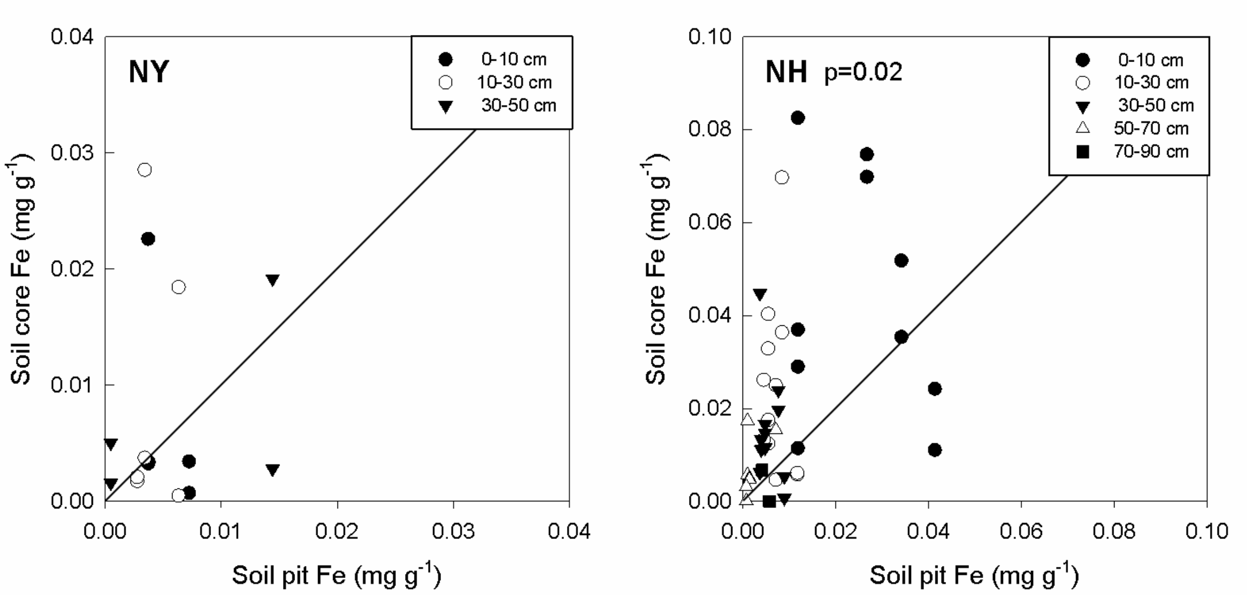


Figure 10. Soil pit Fe concentrations (mg g$^{-1}$) plotted against soil core Fe concentrations at the NY and NH study sites. The lines represent a 1:1 relationship. This element was not analyzed for the CA and NV sites.

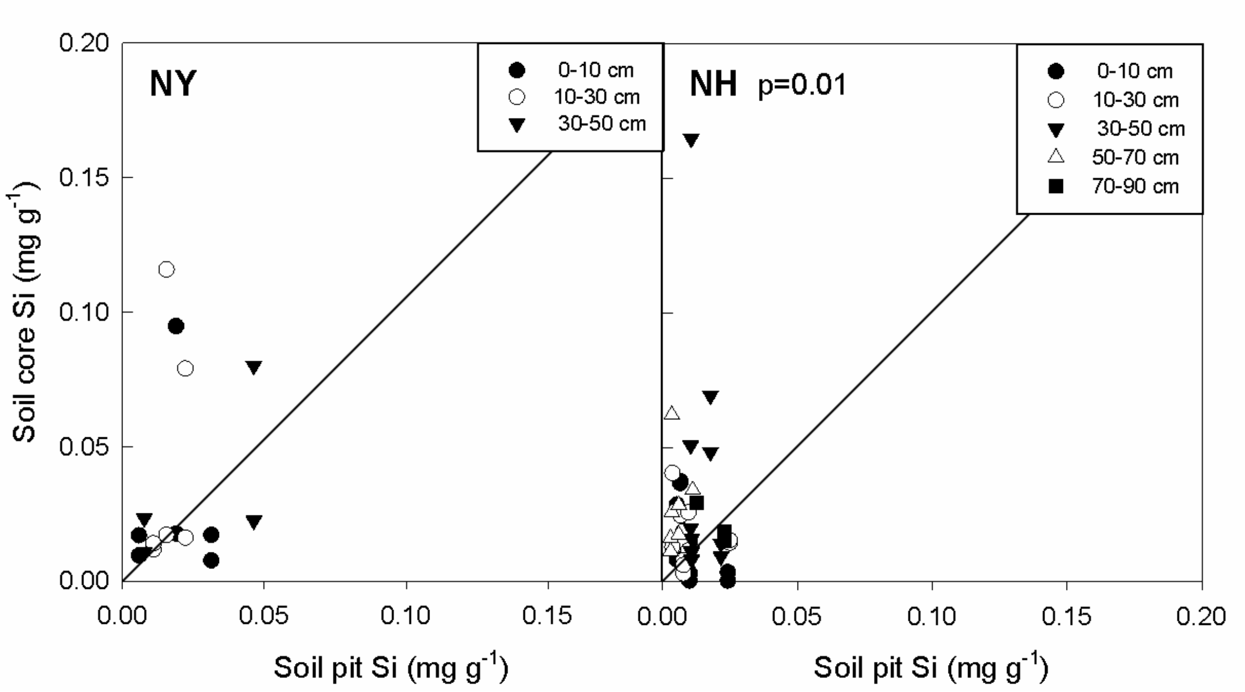


Figure 11. Soil pit Si concentrations (mg g$^{-1}$) plotted against soil core Si concentrations at the NY and NH study sites. The lines represent a 1:1 relationship. This element was not analyzed for the CA and NV sites.

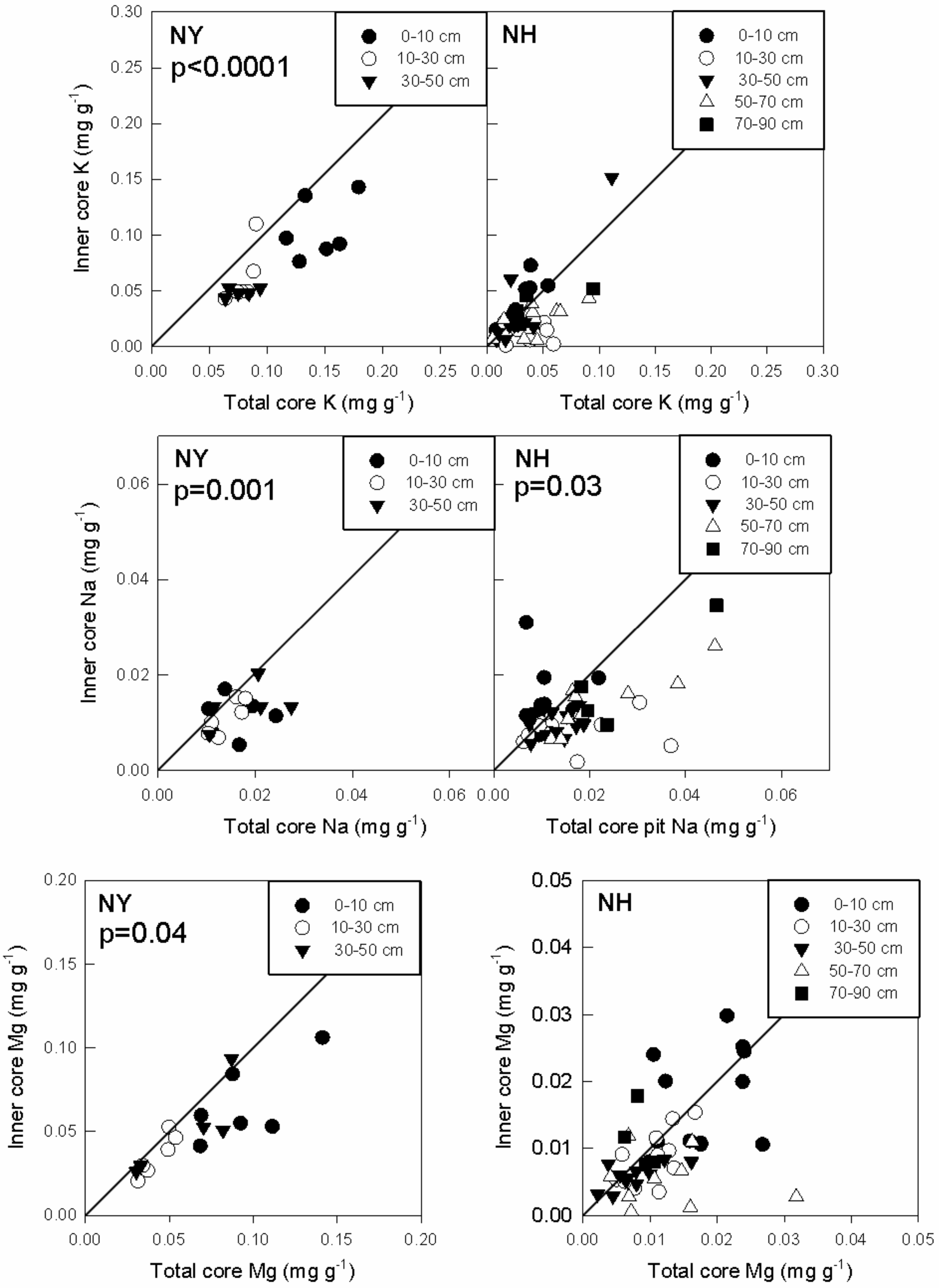


Figure 12. Concentrations of K, Na, Mg (mg $g^{-1}$) in the inner core and total core samples at the NY and NH sites. The lines represent a 1:1 relationship.

## 6. References

Andraski, B.J. 1991. Balloon and core sampling for determining bulk density of alluvial desert soil. Soil Science Society of America Journal 55:1188–1190.

Aichi, H., Y. Fouad, C. Walter, R.A. Viscarra Rossel, Z.L. Chabaane, and M. Sanaa. 2009. Regional predictions of soil organic carbon content from spectral reflectance measurements. Biosystems Engineering 104:442-446.

Bailey, A.S., J.W. Hornbeck, J.L. Campbell, and C. Eagar. 2003. Hydrometeorological database for Hubbard Brook Experimental Forest: 1955-2000. USDA Forest Service, Northeastern Research Station, Gen. Tech. Report NE-305. 36 pp.

Boone, R.D., D.F. Grigal, P. Sollins, R.J. Ahrens, and D.E. Armstrong. 1999. Soil sampling, preparation, archiving, and quality control. In G. P. Robertson et al. (ed.) Standard soil methods for Long-term Ecological Research. Oxford University Press, New York. p 3–28.

Bormann, F.H., G.E. Likens and J.M. Melillo. 1977. Nitrogen budget for an aggrading northern hardwood forest ecosystem. Science 196(4293):981-983.

Carter, R.E. and L.E. Lowe. 1986. Lateral variability of forest floor properties under second-growth Douglas fir stands and the usefulness of composite sampling techniques. Canadian Journal of Forest Research 16(5):1128-1132.

Conant, R.T., G.R. Smith, and K. Paustian. 2003. Spatial Variability of Soil Carbon in Forested and Cultivated Sites: Implications for Change Detection. Journal of Environmental Quality 32(1):278-286.

Conant, R.T., K. Paustian, and E.T. Elliott. 2001. Grassland management and conversion into grassland: Effects on soil carbon. Ecological Applications 11:343-355.

Corti, G., F.C. Ugolini, and A. Agnelli. 1998. Classing the Soil Skeleton (Greater than Two Millimeters): Proposed Approach and Procedure. Soil Science Society of America Journal 62:1620-1629.

Fahey T.J., T.G. Siccama, C.T. Driscoll, G.E. Likens, J. Campbell, C.E. Johnson, J.J. Battles, J.D. Aber, J.J. Cole, M.C. Fisk, P.M. Groffman, R.T. Holmes, P.A. Schwarz, and R.D. Yanai. 2005. The biogeochemistry of carbon at Hubbard Brook. Biogeochemistry 75:109–76.

Fatemi, F.R., R.D. Yanai, S.P. Hamburg, M.A. Vadeboncoeur, M.A. Arthur, R.D. Briggs, and C.R. Levine. 2011. Allometric equations for young northern hardwoods: the importance of age-specific equations for estimating aboveground biomass. Canadian Journal of Forest Research 41:881-891.

Grigal, D.F., R.E. McRoberts, and L.F. Ohmann. 1991. Spatial variation in chemical properties of forest floor and surface mineral soil in the North Central United States. Soil Science 151:282-290.

Hamburg, S.P. 1984. Effects of forest growth on soil nitrogen and organic matter pools following release from subsistence agriculture. In: Stone EL, Eds. Forest soils and treatment impacts. Proceedings of the Sixth North American Forest Soils Conference. Knoxville (TH): University of Tennessee. p 145–58.

Hamburg, S.P., R.D. Yanai, M.A. Vadeboncoeur, M.A. Arthur, C.B. Fuss, and T.G. Siccama. From Missing Source to Missing Sink: Long-term Nitrogen Dynamics in the Northern Hardwood Forest. *In preparation*.

Harmon, M.E., D.L. Phillips, J.J. Battles, A. Rassweiler, R.O. Hall, and W.K. Lauenroth. 2007. Quantifying uncertainty in net primary production measurements. In: Fahey T.J., Knapp A.K. (eds.) Principles and standards for measuring primary production. New York: Oxford University. p 238–60.

Harrison, R., D.D. Richter, and T. Fox. 2011. Deep Soils. Forest Science vol. 57 (1) pp. 1-2.

Harrison, R.B., A.B. Adams, C. Licata, B. Flaming, G.L. Wagoner, P. Carpenter, and E.D. Vance. 2003. Quantifying deep-soil and coarse fractions: avoiding sampling bias. Soil Science Society of America Journal 67:1602-1606.

Harrison, R.B., P.W. Footen, and B.D. Strahm. 2011. Deep Soil Horizons: Contribution and Importance to Soil Carbon Pools and in Assessing Whole-Ecosystem Response to Management and Global Change. Forest Science 57(1):67-76.

Hawley, G.J., P.G. Schaberg, C. Eagar, and C.H. Borer. 2006. Calcium addition at the Hubbard Brook Experimental Forest reduced winter injury to red spruce in a high-injury year. Canadian Journal of Forest Research 36(10):2544-2549.

Huntington, T.G., D.F. Ryan, and S.P. Hamburg. 1988. Estimating soil-nitrogen and carbon pools in a northern hardwood forest ecosystem. Soil Science Society of America Journal 52(4):1162-1167.

Johnson, C.E., A.H. Johnson, and T.G. Siccama. 1991. Whole-tree clear-cutting effects on exchangeable cations and soil acidity. Soil Science Society of America Journal 55:502-508.

Johnson, C.E., A.H Johnson, and T.G Huntington 1991. Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Science Society of America Journal 55:497-502.

Johnson, D.W., J.D. Knoepp, W.T. Swank, J. Shan, L.A. Morris, D.H. Van Lear, and P.R. Kapeluck. 2002. Effects of forest management on soil carbon: results of some long-term resampling studies. Environmental Pollution 116: S201-S208.

Johnson, D.W., J.D. Murphy, B.M. Rau, and W.W. Miller. 2011. Subsurface Carbon Contents:

Some Case Studies in Forest Soils. Forest Science 57(1):3-10.

Johnson, D.W., J.D. Murphy, R.B. Susfalk, T.G. Caldwell, W.W. Miller, R.F. Walker, and R.F. Powers. 2005. The effects of wildfire, salvage logging, and post-fire N-fixation on the nutrient budgets of a Sierran forest. Forest Ecology and Management 220:155-165.

Juice, S.M., T.J. Fahey, T.G. Siccama, C.T. Driscoll, E.G. Denny, C. Eagar, N.L. Cleavitt, R. Minocha, and A.D. Richardson. 2006. Response of sugar maple to calcium addition to northern hardwood forest. Ecology 87(5):1267-1280.

Jurgensen, M.F., M.J. Larsen, and A.E. Harvey. 1977. A soil sampler for steep, rocky sites. Res. Note INT-217. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 4 pp.

Kulmatiski, A., D.J. Vogt, T.G. Siccama, J.P. Tilley, K. Kolesinskas, T.W. Wickwire, B.C. Larson. 2004. Landscape determinants of soil carbon and nitrogen storage in southern New England. Soil Science Society of America Journal 68(6):2014-2022.

Kulmatiski, A., D.J. Vogt, T.G. Siccama, and K.H. Beard. 2003. Detecting nutrient pool changes in rocky soils. Soil Science Society of America Journal 67(4):1282-1286.

Lehrter, J.C. and C. Just. 2010. Uncertainty propagation in an ecosystem nutrient budget. Ecological Applications 20:508-524.

Li, J., D.D. Richter, A. Mendoza, and P. Heine 2010. Effects of land-use history on soil spatial heterogeneity of macro- and trace elements in the Southern Piedmont USA. Geoderma 156:60–73.

Lichter, J.M., and L.R. Costello. 1994. An evaluation of volume excavation and core sampling techniques for measuring soil bulk density. Journal of Arboriculture 20:160-164.

Likens, G.E. and F.H. Bormann. 1970. Chemical analyses of plant tissues from the Hubbard Brook ecosystem in New Hampshire. Yale University School of Forestry Bulletin 79. 25 pp.

Likens, G.E., C.T. Driscoll, D.C. Buso, T.G. Siccama, C.E. Johnson, G.M. Lovett, T.J. Fahey, W.A. Reiners, D.F. Ryan, C.W. Martin, and S.W. Bailey. 1998. The biogeochemistry of calcium at Hubbard Brook. Biogeochemistry 41(2):89-173.

Lundell, Y. 1987. Nutrient variation in forest soil samples due to time of sampling and method of storage. Plant and Soil 98(3):363-375.

Lyons, J.B., W.A. Bothner, R.H. Moench, and J.B. Thompson, Jr. 1997. Bedrock geologic map of New Hampshire. U.S. Geol. Surv. scale, 1 : 250,000, 2 pls.

McBratney, A.B., and R. Webster. 1983. How many observations are needed for regional estimation of soil properties? Soil Science 135:177-183.

Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carroll, R.R. Blank. 2006. Wildfire effects on soil nutrients and leaching in a Tahoe Basin Watershed. Journal of Environmental Quality 35:479–489.

Nezat, C., J. Blum, R.D. Yanai, and S.P. Hamburg. 2007. A sequential extraction to determine the distribution of apatite in granitoid soil mineral pools with application to weathering at the Hubbard Brook Experimental Forest, NH, USA. Applied Geochemistry 22(11):2406-2421.

Page-Dumroese, D.S., M.F. Jurgensen, R.E. Brown, and G.D. Mroz. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Science Society of America Journal 63:379-383.

Ponder, F., and D.E. Alley. 1997. Soil sampler for rocky soils. Research Note NC-371. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 5 pp.

Post, W. and K. Kwon. 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6:317–328.

Rau, B.M., D.W. Johnson, J.C. Chambers, R.R. Blank, and A. Lucchesi. 2009. Estimating root biomass and distribution after fire in a Great Basin woodland using cores and pits. Western North American Naturalist 69(4):459-468.

Rau, B.M., A. Melvin, D.W. Johnson, C.L. Goodale, D.E. Todd, and R.R. Blank. 2011. Revisiting Soil Nutrient Sampling: Quantitative Pits vs. Rotary Cores Soil Science. Soil Science 176(6): 273-279.

Richter, D.D. and M.L. Mobley. 2009. Monitoring the Earth’s critical zone. Science 326:1067-1068.

Richter, D.D., D. Markewitz, P.R. Heine, V. Jin, J. Raikes, K. Tian, and C.G. Wells. 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. Forest Ecology and Management 138: 233-248.

Richter, D.D., M. Hofmockel, M.A. Callaham, D.S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing Earth’s rapidly changing ecosystems. Soil Science Society of America Journal 71:266–279.

Roskoski, J.P. 1980. Nitrogen fixation in hardwood forests of the northeastern United States. Plant and Soil 54(1):33-44.

Stone, E.L. 1975. Species effects on nutrient cycles and soil change. Philosophical Transactions of the Royal Society B: Biological Sciences 371:149-162.

Suarez E.R., T.J. Fahey, P.M. Groffman, P.J. Bohlen, and M.C. Fisk. 2004. Effects of exotic earthworms on soil phosphorus cycling in two broadleaf temperate forests. Ecosystems 7:28–44.

Sucre, E.B., J.W. Tuttle, and T.R. Fox. 2011. The Use of Ground-Penetrating Radar to Accurately Estimate Soil Depth in Rocky Forest Soils. Forest Science 57(1):59-66.

Ugolini, F.C., G. Corti, A. Agnelli, and F. Piccardi. 1996. Mineralogical, physical and chemical properties of rock fragments in soil. Soil Science 161:521-542.

Vadeboncoeur, M.A., S.P. Hamburg, M.J. Pennino, J.D. Blum, E.B. O'Donnell, R.D. Yanai. Measuring long-term changes in forest soils: Have 30 years of quantitative pit data made a difference? *In preparation.*

West, T.O. and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66:1930-1946.

Whitney, N. and D. Zabowski. 2004. Total soil nitrogen in the coarse fraction and at depth. Soil Science Society of America Journal 68:612-619.

Wielopolski, L., G. Hendrey, K. Johnsen, S. Mitra, S.A. Prior, H.H. Rogers, H.A. Torbert. 2008. Non-destructive system for analyzing carbon in the soil. Soil Science Society of America Journal 72:1269–1277.

Wielopolski, L., R.D. Yanai, C.R. Levine, M.A. Vadeboncoeur, S. Mitra. 2010. Rapid, Non-destructive Carbon Analysis of Forest Soils Using Neutron-induced Gamma-Ray Spectroscopy. Forest Ecology and Management 206(7):1132-1137.

Yanai, R.D. 1992. Phosphorus Budget of a 70-Year-Old Forest. Biogeochemistry 17(1):1-22.

Yanai, R.D., T.G. Siccama, M.A. Arthur, C.A. Federer, and A.J. Friedland. 1999. Accumulation and depletion of base cations in forest floors in the northeastern US. Ecology 80:2774-2787.

Yanai, R.D., S.V. Stehman, M.A. Arthur, C.E. Prescott, A.J. Friedland, T.G. Siccama, and D. Binkley. 2003. Detecting change in forest floor carbon. Soil Science Society of America Journal 67:1583-1593.

Yanai, R.D., J.J. Battles, A.D. Richardson, E.B. Rastetter, D.M. Wood, and C. Blodgett. 2010. Estimating uncertainty in ecosystem budget calculations. Ecosystems 13(2): 239-248

Zabowski, D., N. Whitney, J. Gurung, and J. Hatten. 2011. Total Soil Carbon in the Coarse Fraction and at Depth. Forest Science 57(1):11-18.

# 7. Appendices

Appendix I. Table showing the corresponding depths of soil pit and soil core increments at the NH sites (Stands C6 and C8). At the NH site, mineral soil in the soil pits was measured first by a 10 cm depth increment, then in 20 cm increments to the C horizon. After hitting the C horizon, soil was measured to a 25 cm depth into the C horizon. The soil cores were not delineated by horizon, and thus do not always precisely correspond to the depth increment of the soil pit. This data is not available for the NY site because the depth of the core was not measured after each sequential depth increment.

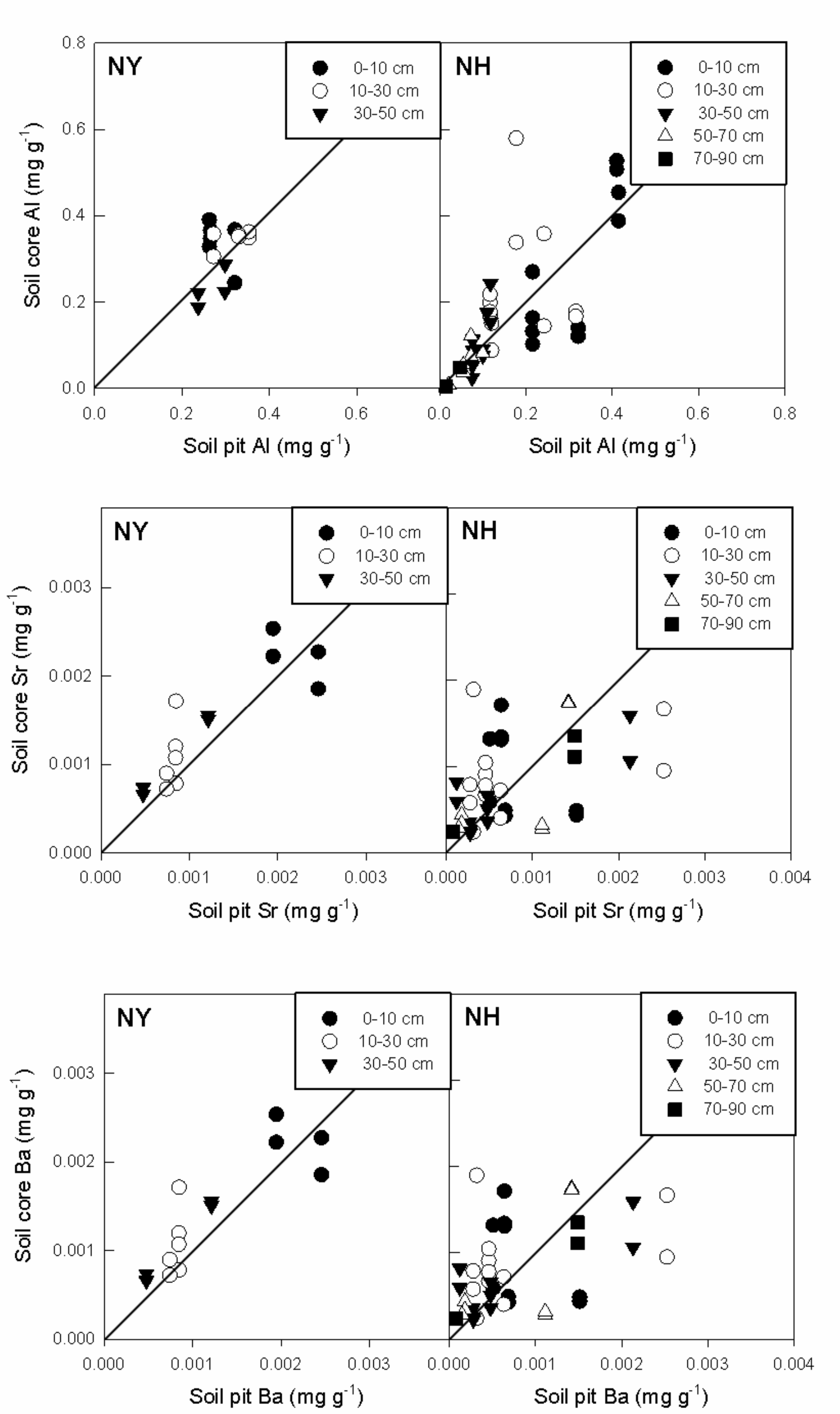
| Site | Stand | Pit | # of cores at that depth | Core depth (cm) | Pit depth | Pit: actual depth of layer (c |
|---|---|---|---|---|---|---|
| NH | C6 | 1 | 2 | 0-10 | 0-10 | 0-9.6 |
| NH | C6 | 1 | 2 | 10-30 | 10-30 | 9.6-24.3 |
| NH | C6 | 1 | 2 | 30-50 | C (0-25) | 24.3-48.6 |
| NH | C6 | 1 | 2 | 50-70 | C (25-50) | 48.6-73.5 |
| NH | C6 | 2 | 2 | 0-10 | 0-10 | 0-10.4 |
| NH | C6 | 2 | 2 | 10-30 | 10-30 | 10.4-26.0 |
| NH | C6 | 2 | 2 | 30-50 | 30-50 | 26.0-47.0 |
| NH | C6 | 2 | 1 | 50-70 | 50-C | 47.0-74.0 |
| NH | C6 | 2 | 1 | 70-90 | C (0-25) | 74.0-99.5 |
| NH | C6 | 3 | 1 | 0-10 | 0-10 | 0-9.8 |
| NH | C6 | 3 | 2 | 10-30 | 10-30 | 9.8-16.8 |
| NH | C6 | 3 | 2 | 30-50 | C (0-25) | 16.8-41.7 |
| NH | C8 | 1 | 4 | 0-10 | 0-10 | 0-12.0 |
| NH | C8 | 1 | 4 | 10-30 | 10-30 | 12.0-30.5 |
| NH | C8 | 1 | 3 | 30-50 | 30-50 | 30.5-51.8 |
| NH | C8 | 1 | 1 | 50-70 | 50-C | 51.8-75.6 |
| NH | C8 | 1 | 1 | 70-90 | C (0-25) | 75.6-97.6 |
| NH | C8 | 2 | 2 | 0-10 | 0-10 | 0-9.7 |
| NH | C8 | 2 | 2 | 10-30 | 10-30 | 9.7-31.6 |
| NH | C8 | 2 | 2 | 30-50 | 30-50 | 31.6-40.6 |
| NH | C8 | 2 | 2 | 50-70 | C (0-25) | 40.6-68.8 |
| NH | C8 | 2 | 2 | 70-90 | C (25-50) | 68.8-90.0 |

Appendix II. Table showing the corresponding depths of soil pit and soil core increments at the CA sites. Depth was measured after every sequential increment was extracted.

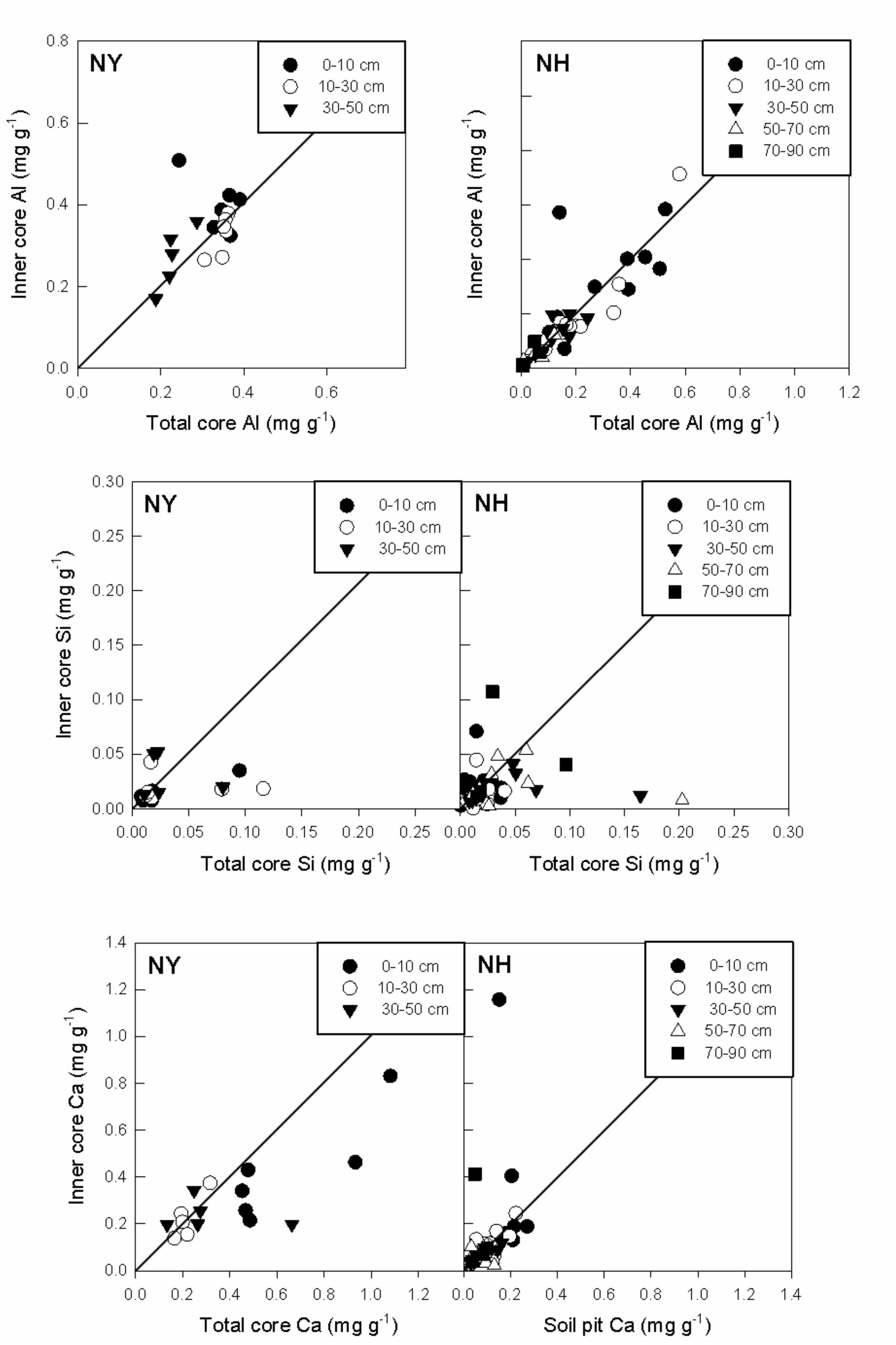
| Site | Pit | Depth Increment (cm) | Core depth (cm) | Pit depth (cm) |
|---|---|---|---|---|
| CA | 22 | 0-20 | 0-20 | 0-20 |
| CA | 22 | 20-40 | 20-41 | 20-40 |
| CA | 22 | 40-60 | 41-58 | 40-60 |
| CA | 23 | 0-20 | 0-20 | 0-20 |
| CA | 23 | 20-40 | 20-41 | 20-40 |
| CA | 23 | 40-60 | 41-60 | 40-60 |
| CA | 24 | 0-20 | 0-19 | 0-20 |
| CA | 24 | 20-40 | 19-41 | 20-40 |
| CA | 24 | 40-60 | 41-61 | 40-60 |
| CA | 25 | 0-20 | 0-19 | 0-20 |
| CA | 25 | 20-40 | 19-40 | 20-40 |
| CA | 25 | 40-60 | 40-59 | 40-60 |

Appendix III. Table showing the corresponding depths of soil pit and soil core increments at the NV sites. Depth was measured after every sequential increment was extracted.

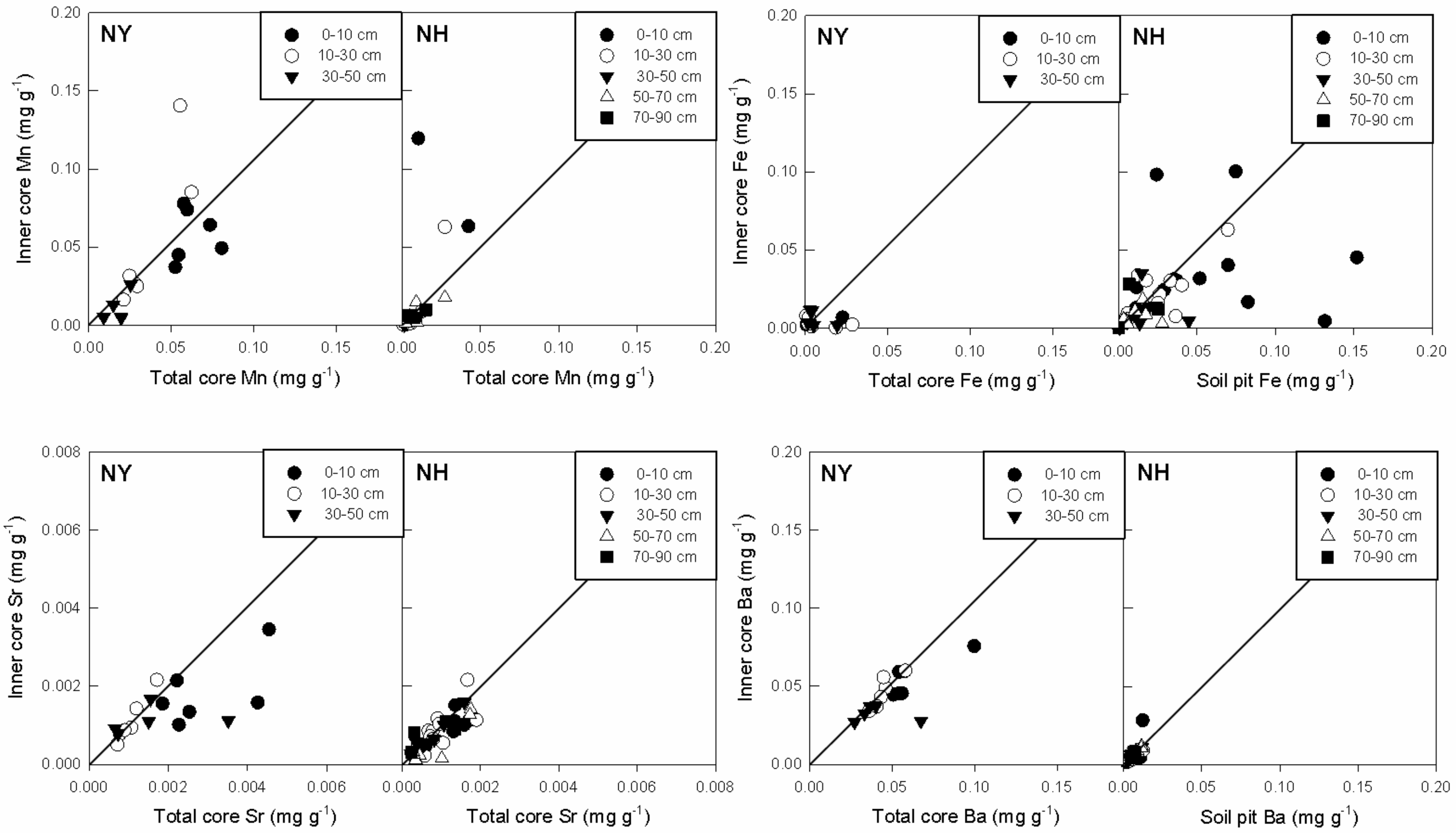
| Site | Pit | Depth Increment (cm) | Core Depth (cm) | Pit Depth (cm) |
|---|---|---|---|---|
| NV | 1 | 0-8 | 0-12 | 0-8 |
| NV | 1 | 8-23 | 12-23 | 8-23 |
| NV | 1 | 23-38 | 23-35 | 23-38 |
| NV | 1 | 38-52 | 35-51 | 38-52 |
| NV | 2 | 0-8 | 0-8 | 0-8 |
| NV | 2 | 8-23 | 8-24 | 8-23 |
| NV | 2 | 23-38 | 24-38 | 23-38 |
| NV | 2 | 38-52 | 38-52 | 38-52 |
| NV | 3 | 0-8 | 0-8 | 0-8 |
| NV | 3 | 8-23 | 8-28 | 8-23 |
| NV | 3 | 23-38 | 28-38 | 23-38 |
| NV | 3 | 38-52 | 38-56 | 38-52 |
| NV | 4 | 0-8 | 0-10 | 0-8 |
| NV | 4 | 8-23 | 10-24 | 8-23 |
| NV | 4 | 23-38 | 24-34 | 23-38 |
| NV | 4 | 38-52 | 34-44 | 38-52 |
| NV | 5 | 0-8 | 0-9 | 0-8 |
| NV | 5 | 8-23 | 9-24 | 8-23 |
| NV | 5 | 23-38 | 24-35 | 23-38 |
| NV | 5 | 38-52 | 35-52 | 38-52 |
| NV | 6 | 0-8 | 0-12 | 0-8 |
| NV | 6 | 8-23 | 12-24 | 8-23 |
| NV | 6 | 23-38 | 24-35 | 23-38 |
| NV | 6 | 38-52 | 35-50 | 38-52 |
| NV | 7 | 0-8 | 0-8 | 0-8 |
| NV | 7 | 8-23 | 8-24 | 8-23 |
| NV | 7 | 23-38 | 24-41 | 23-38 |
| NV | 7 | 38-52 | 41-49 | 38-52 |
| NV | 8 | 0-8 | 0-11 | 0-8 |
| NV | 8 | 8-23 | 11-24 | 8-23 |
| NV | 8 | 23-38 | 24-38 | 23-38 |
| NV | 8 | 38-52 | 38-55 | 38-52 |
| NV | 9 | 0-8 | 0-10 | 0-8 |
| NV | 9 | 8-23 | 10-24 | 23-38 |
| NV | 9 | 23-38 | 24-38 | 38-52 |
| NV | 9 | 38-52 | 38-51 | 8-23 |



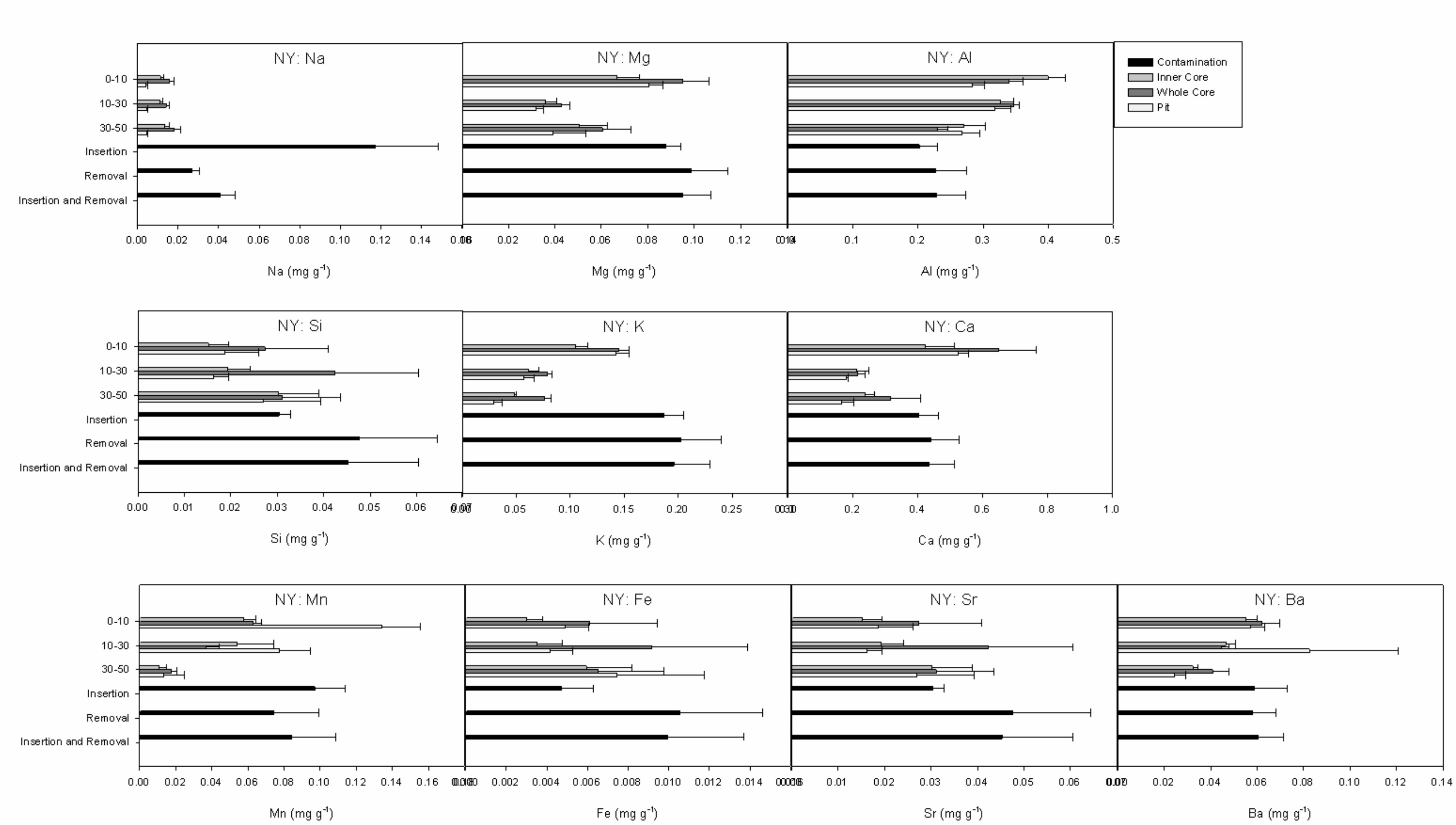
Appendix IV. Concentrations of Al, Sr, and Ba (mg g$^{-1}$) in the pit samples plotted against concentrations in the core samples at the NY and NH sites. The lines represent a 1:1 relationship. There were no significant differences between pits and cores for either of these elements at either site.



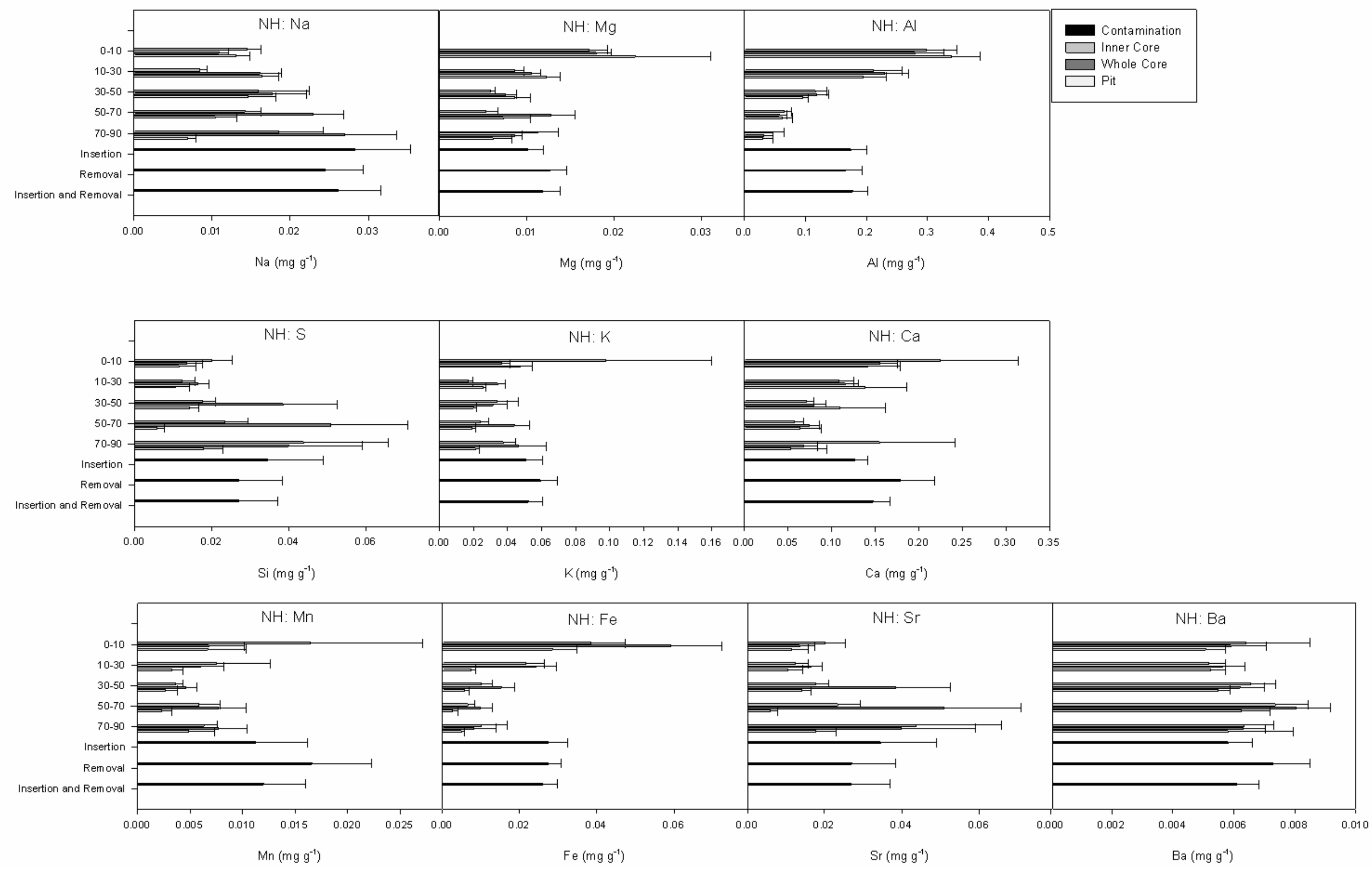
Appendix V. Concentrations of Al, Si, and Ca **(**mg g$^{-1}$) in the total core samples plotted against concentrations in the inner core samples at the NY and NH sites. The lines represent a 1:1 relationship. There were no significant differences between pits and cores for any of these elements at either site.



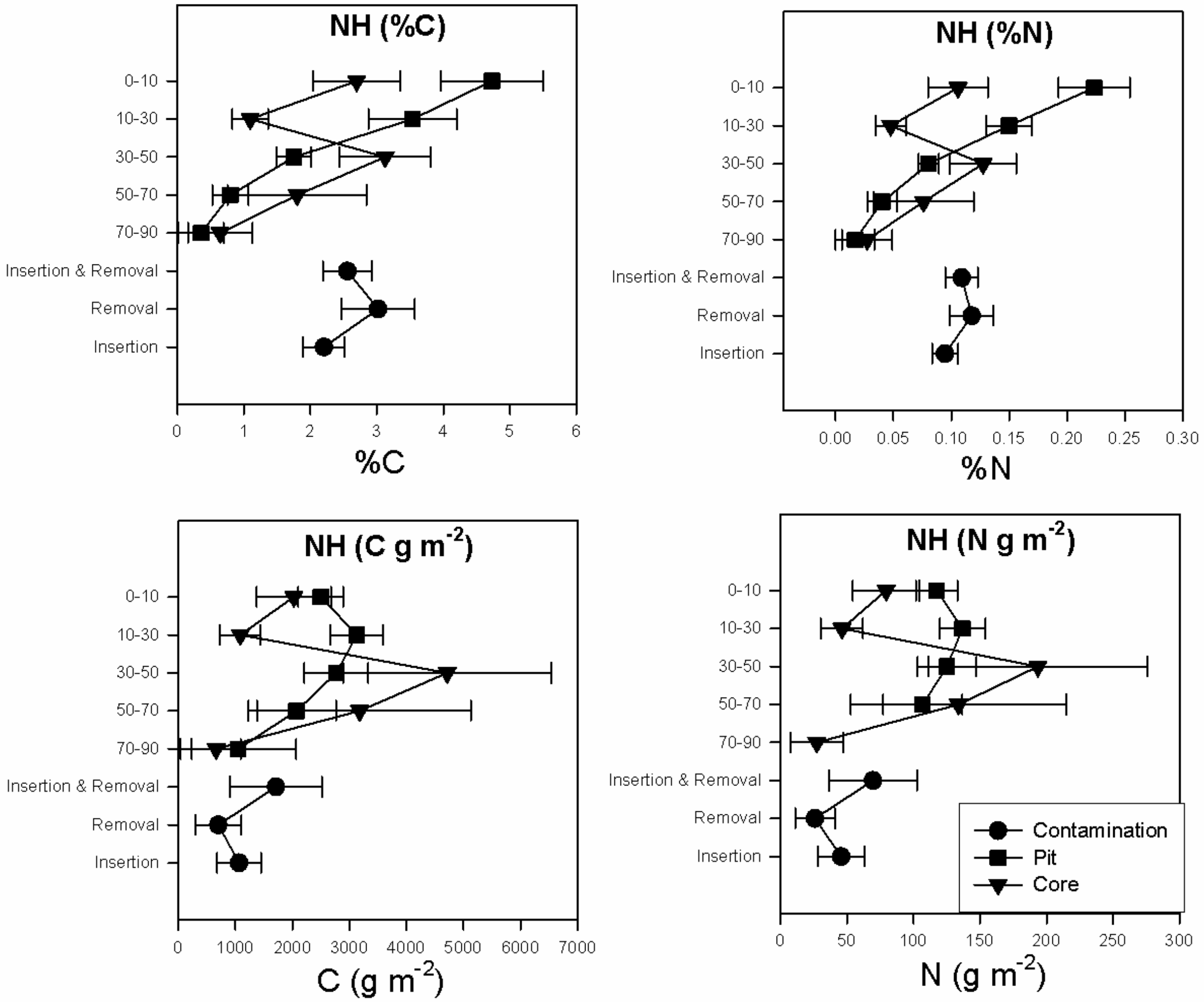
Appendix VI. Concentrations of Mn, Fe, Sr, and Ba (mg g$^{-1}$) in the total core samples plotted against concentrations in the inner core samples at the NY and NH sites. The lines represent a 1:1 relationship. There were no significant differences between pits and cores for any of these elements at either site.



Appendix VII. Concentrations of Na, Mg, Al, Si, K, Ca, Mn, Fe, Sr, and Ba **(**mg $g^{-1}$) in the total core samples with contamination, the total core without contamination, the inner core, and the soil pit NY site. Cores and pit are shown by depth, and the contamination for the total profile is shown below the depth increments. The contamination typically resembles the concentrations observed in the upper 30 cm of soil.



Appendix VIII. Concentrations of Na, Mg, Al, Si, K, Ca, Mn, Fe, Sr, and Ba (mg $g^{-1}$) in the total core samples with contamination, the total core without contamination, the inner core, and the soil pit NH site. Cores and pit are shown by depth, and the contamination for the total profile is shown below the depth increments. The lines represent a 1:1 relationship. The contamination typically resembles the concentrations observed in the upper 30 cm of soil.



Appendix IX. Concentration (%) and content (g m$^{-2}$) of C and N in soil cores, soil pits, and contamination sources at the NH site.

# 8. Vita

**Carrie Rose Levine**
State University of New York, College of Environmental Science and Forestry
Department of Forest and Natural Resources Management
208 Marshall Hall · 1 Forestry Dr. · Syracuse, NY 13210 USA
crlevi01@syr.edu
773.307.2583

## EDUCATION

| | |
|---|---|
| 2011 | State University of New York, College of Environmental Science and Forestry, Syracuse, NY<br>Department of Forest and Natural Resource Management<br>MS, Forest Ecosystem Science |
| 2009 | Vassar College, Poughkeepsie, NY<br>BA, Biology |

## PROFESSIONAL EXPERIENCE

| | |
|---|---|
| 2011-present | Research Fellow, New York State Energy Research and Development Authority |
| 2011-present | Research assistant; Quantifying Uncertainty in Ecosystem Studies (QUEST) |
| 2009-2010 | Research assistant; supervised by Ruth Yanai<br>SUNY-ESF, Syracuse, New York |
| 2010 | Teaching assistant; Meteorology (FOR 338/538)<br>SUNY-ESF, Syracuse, New York |
| 2009 | Teaching assistant; Forest Ecology (FOR 332/532)<br>SUNY-ESF, Syracuse, New York |

## PUBLICATIONS

**Levine, C.R.**, R.J. Winchcombe, C.D. Canham, L.M. Christenson, M.L. Ronsheim. Effects of deer exclusion on seed banks and sapling regeneration in northeast forests. *In press, Northeastern Naturalist.*

Yanai, R.D., M.A. Arthur, M. Acker, **C.R. Levine**, B.B. Park. Variation in mass and nutrient concentration of leaf litter across years and sites in New Hampshire northern hardwoods. *In revision, Canadian Journal of Forest Research.*

Fatemi, F.R., R.D. Yanai, S.P. Hamburg, M.A. Vadeboncoeur, M.A. Arthur, R.D. Briggs, **C.R. Levine**. 2011. The Influence of Stand Age on Aboveground Allometry of Northern Hardwood Tree Species. Canadian Journal of Forest Research 41:881-891.

Wielopolski, L., R.D. Yanai, **C.R. Levine**, M.A. Vadeboncoeur, S. Mitra. 2010. Rapid, Non-destructive Carbon Analysis of Forest Soils Using Neutron-induced Gamma-Ray Spectroscopy. Forest Ecology and Management 206(7):1132-1137.

## PRESENTATIONS

July 12, 2011. **C.R. Levine,** J.L. Campbell, M.B. Green, R.D. Yanai, M.B. Adams, D.A. Burns, D.C. Buso, M.E. Harmon, T. Keenan, S.L. LaDeau, G.E. Likens, W.H. McDowell, J.N. Parman, S.D. Sebestyen, J. Vose, M. Williams. Quantifynig Uncertainty in Ecosystem Studies (QUEST): A cross-site comparison of watershed input-output budgets. The Ecological Society of America Annual Meeting, Austin, TX.

July 11, 2011. Green, M.B., D.C. Buso, J.L. Campbell, **C.R. Levine,** G.E. Likens, R.D. Yanai. Long-term trends in uncertainty of element fluxes at the Hubbard Brook Experimental Forest. The Ecological Society of America Annual Meeting, Austin, TX.

July 11, 2011. Rothfuss Dair, B. **C.R. Levine,** M.C. Fisk. Nitrogen and phosphorus co-limitation of microbes in soil microcosms. Poster presented at the Ecological Society of American Annual Meeting, Austin, TX.

July 6, 2011. **Levine, C.R.,** R.D. Yanai, M.B. Green, J. Campbell, G.E. Likens, D. Buso. QUEST: Quantifying uncertainty in Ecosystem Studies. Hubbard Brook Ecosystem Study Annual Cooperators Meeting, West Thornton, NH.

July 6, 2011. Yanai, R.D., N. Tokuchi, M.B. Green, J. Campbell, **C.R. Levine**, E. Matsuzaki. Hubbard Brook, Coweeta, and Wakayama (Japan): Sources of Uncertainty in Stream Export of Nutrients. Hubbard Brook Ecosystem Study Annual Cooperators Meeting, West Thornton, NH.

June 29, 2011. Yanai, R.D., N. Tokuchi, M.B. Green, J. Campbell, **C.R. Levine**, E. Matsuzaki. Nutrient cycling in forest ecosystems: Uncertainty in nutrient budgets. University of Tokyo, Tokyo, Japan.

June 1, 2011. **Levine, C.R.** Quantifying Uncertainty in Ecosystem Studies. Presentation in defense of Masters Thesis, SUNY-ESF, Syracuse, NY.

August 2, 2010**. Levine, C.R**., R.D. Yanai, M.A. Vadeboncouer, and S.P. Hamburg. New techniques in soil sampling: methods for long-term ecological research. Poster presented at the Ecological Society of America Annual Meeting, Pittsburgh, PA.

July 7, 2010. **Levine, C.R**. Aboveground biomass and species composition at young, mid-aged, and mature stands at three sites in the White Mountains. Hubbard Brook Ecosystem Study Annual Cooperators Meeting, West Thornton, NH.

April 12, 2010. **Levine, C.R.**, R.D. Yanai, S.P. Hamburg, M.A. Vadeboncoeur. Developments in soil sampling methods: testing the effects of power coring on several soil properties. Poster presented at SUNY-ESF Spotlight on Graduate Student Research. Syracuse, NY.

January 28, 2010**. Levine, C.R**., R.D. Yanai, S.P. Hamburg, and T.K. Refsland. New techniques in soil sampling: methods for long-term ecological research. Poster presented at Society of American Foresters NY Chapter Annual Meeting. Syracuse, NY.

January 5, 2010. **Levine, C.R**. Estimating uncertainty in the Hubbard Brook phosphorus budget. Hubbard Brook Ecosystem Study Committee of Scientists Meeting. Millbrook, NY.

November 13, 2009. **Levine, C.R**., M. Ronsheim, K. Van Camp, L. Christenson, R. Winchcombe, and C. Canham. White-tailed deer overabundance in the Northeastern US:

Concerns for our future forests. Poster presented at Environmental Consortium of Hudson Valley Colleges and Universities. Poughkeepsie, NY.

November 2, 2009. **Levine, C.R**., R.D. Yanai, S.P. Hamburg, and T.K. Refsland. New techniques in soil sampling: methods for long-term ecological research. Poster presented at American Society of Agronomy - Crop Science Society of America - Soil Science Society of America International Annual Meeting. Pittsburgh, PA.

October 31, 2009. **Levine, C.R**., R.D. Yanai, S.P. Hamburg, and T.K. Refsland. New techniques in soil sampling: methods for long-term ecological research. Poster presented at Rochester Academy of Science Annual Fall Scientific Paper Session, Rochester, NY.

September 12, 2009. **Levine, C.R**., R.D. Yanai, S.P. Hamburg, and T.K. Refsland. New techniques in soil sampling: methods for long-term ecological research. Poster presented at LTER All-Scientists Meeting, Estes Park, CO.

July 6, 2009. **Levine, C.R.** Quick but dirty: Can power coring replace soil pits? Hubbard Brook Ecosystem Study Annual Cooperators Meeting, West Thornton, NH.

May 5, 2009. Christenson, L.M., M. Ronsheim, K. VanCamp, **C.R. Levine**, R. Winchcombe, and C. Canham. What to do with white-tailed deer? How Vassar College is managing. Poster presented at Cary Conference, Cary Institute of Ecosystem Studies, Millbrook, NY.

## WORKSHOPS

July 7, 2011. Quantifying uncertainty in ecological studies. Co-led with Ruth Yanai, Mark Green, and John Campbell at the Ecological Society of American Annual Meeting, Austin, TX.

## GRANTS, AWARDS, AND HONORS

| | |
|---|---|
| 2011 | Albert L. Leaf Memorial Award (Awarded by the Department of Forest and Natural Resources Management, SUNY-ESF) |
| 2011 | C. Eugene Farnsworth Award (Awarded by the Department of Forest and Natural Resources Management, SUNY-ESF) |
| 2011 | SUNY-ESF Graduate Student Travel Grant |
| 2010 | National Garden Club Scholarship |
| 2010 | Alec C. Proskine Award (Awarded by the Department of Forest and Natural Resources Management, SUNY-ESF) |
| 2010 | Edna Bailey Sussman Foundation Fellowship |
| 2010 | SUNY-ESF Graduate Student Travel Grant |
| 2009 | LTER Travel Grant for All Scientists Meeting |
| 2009 | Sigma Xi Honor Society |
| 2009 | Nancy Skinner Clark Fellowship (Awarded by the Biology Department, Vassar College) |

2009 Vassar College Environmental Research Institute Fellowship (Awarded by the Environmental Studies Program, Vassar College)

## PROFESSIONAL ACTIVITIES AND SERVICE

*Society Member*: Ecological Society of America (ESA)

American Society of Agronomy – Crop Science Society of America – Soil Science Society of America (ASA-CSSA-SSSA)

*Reviewer*: Soil Science Society of America Journal